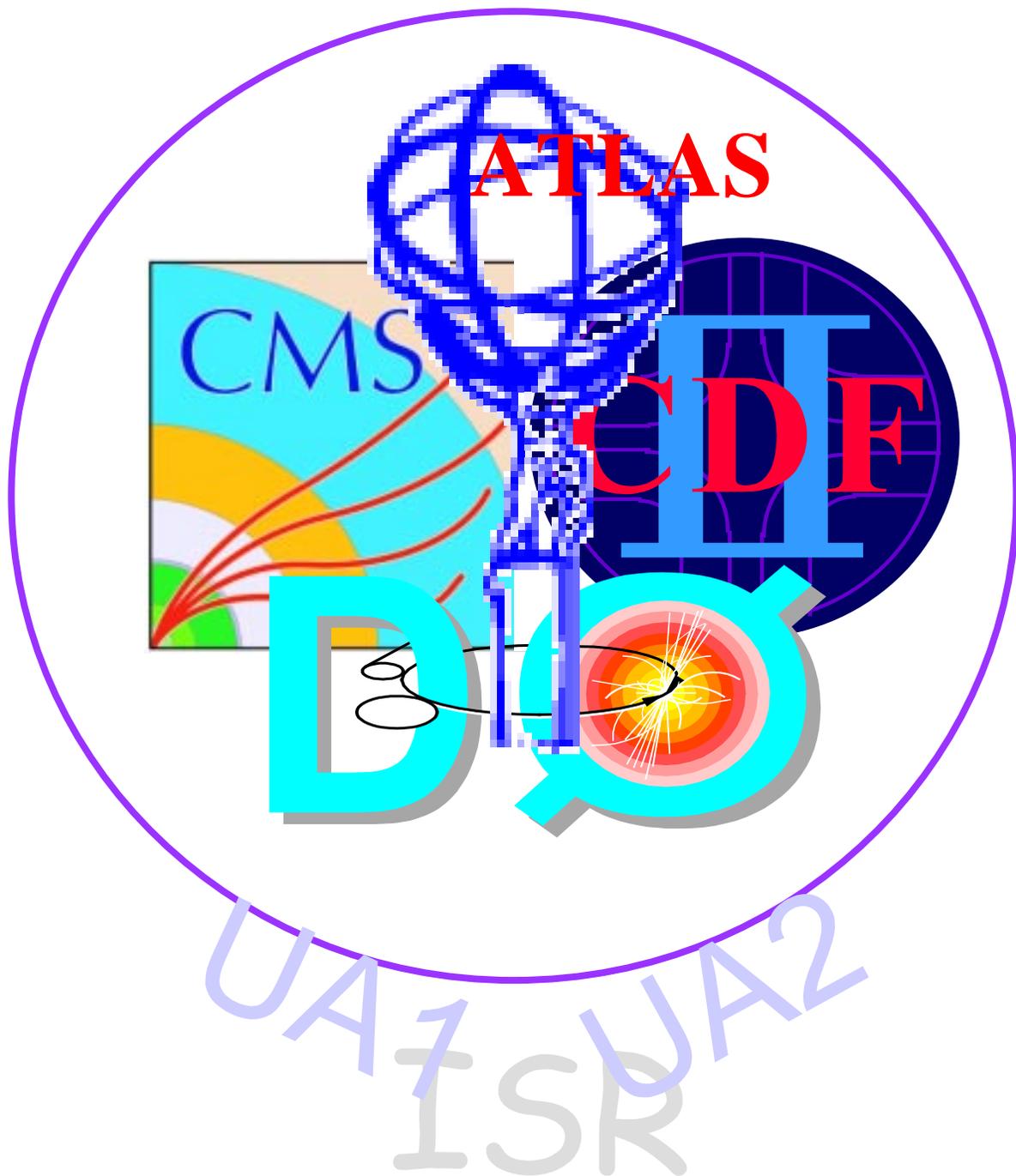


Hadron Collider Detectors



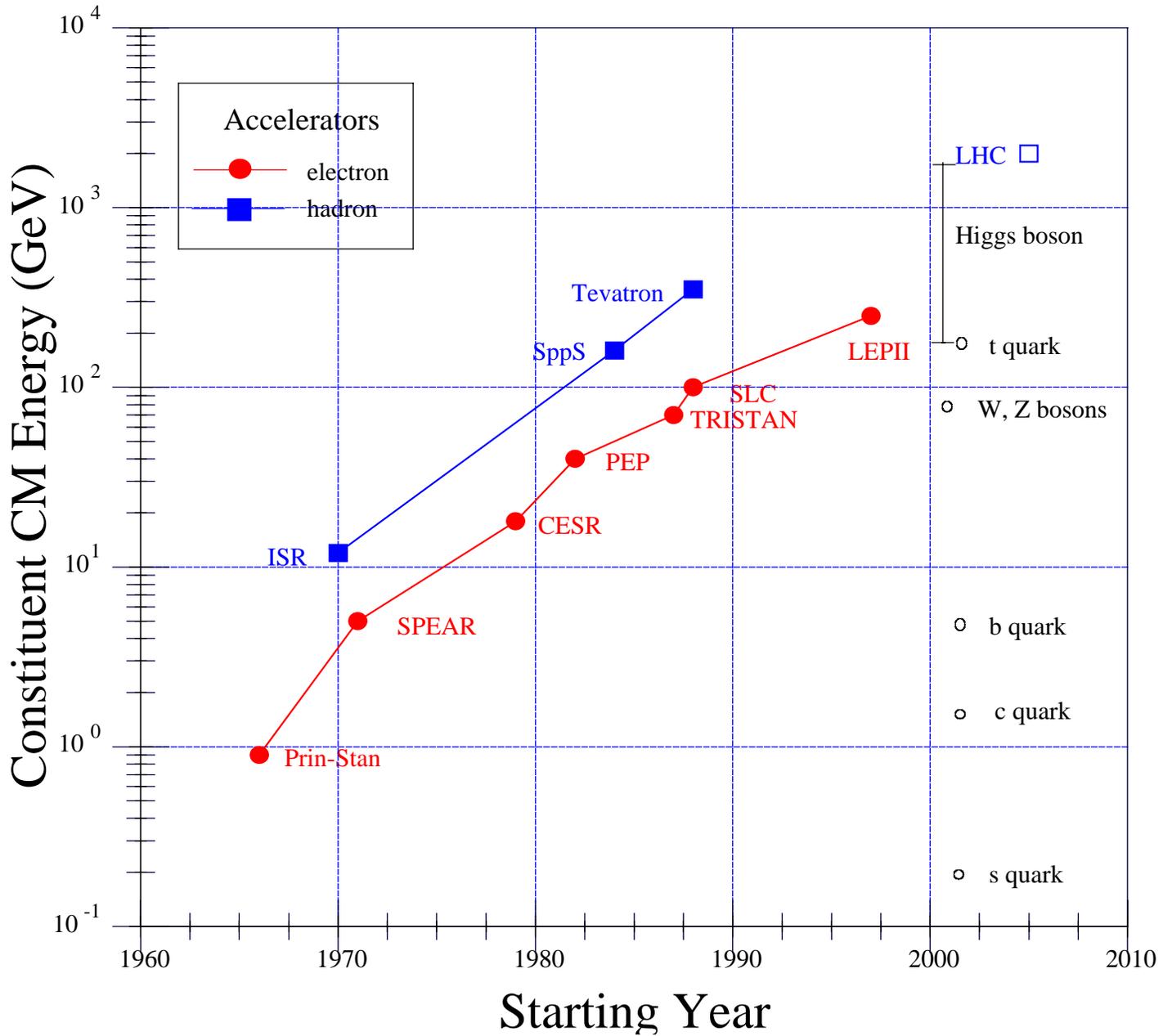
Talk Presented by

J.Incandela/Fermilab

Fermilab Academic Lecture Series; January 19,2000



The Energy Frontier





The Good...

- Higher Energy
- Broadband production
 - multiple production mechanisms
 - quark-quark, glue-gluon, quark-gluon
 - broad range of *CM* energy
 - with high enough luminosity, one can probe realms far above (and below) the average constituent *CM* energy

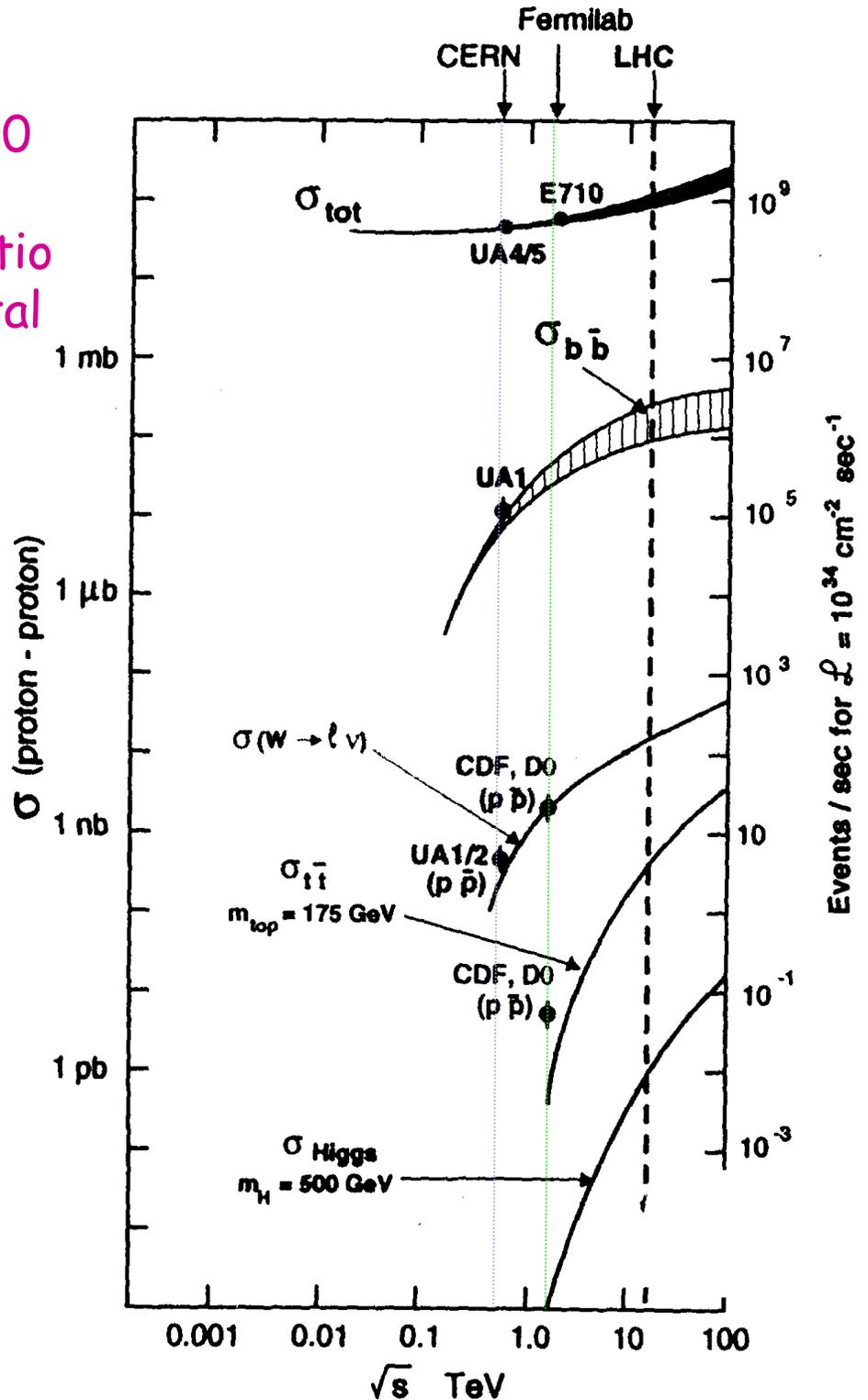
⇒ Discovery machines



...the Bad...

- At the LHC a 500 GeV Higgs has a cross section ratio of $\sim 10^{-11}$ the total cross section.

- σ_{tot}
 - 60 mb @FNAL
 - 100 mb @CERN

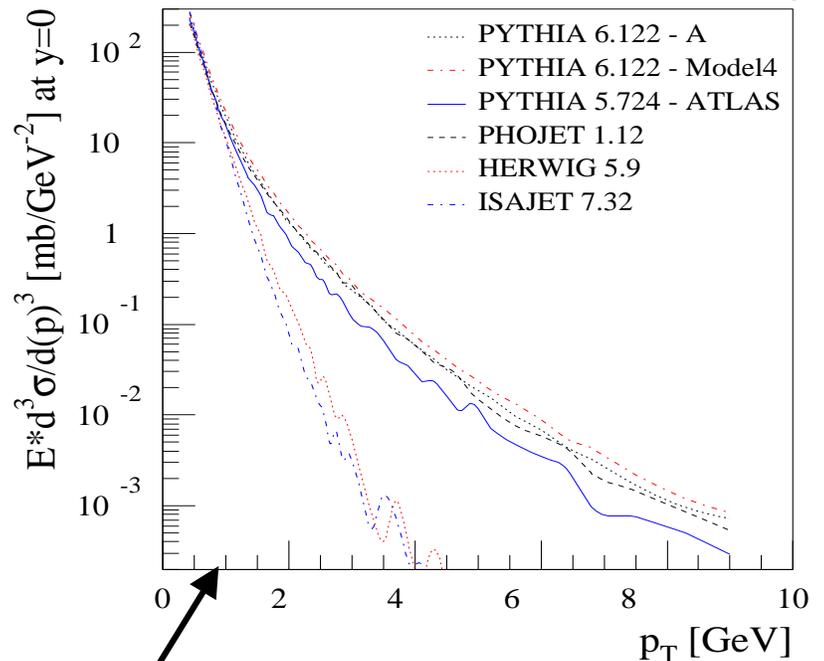
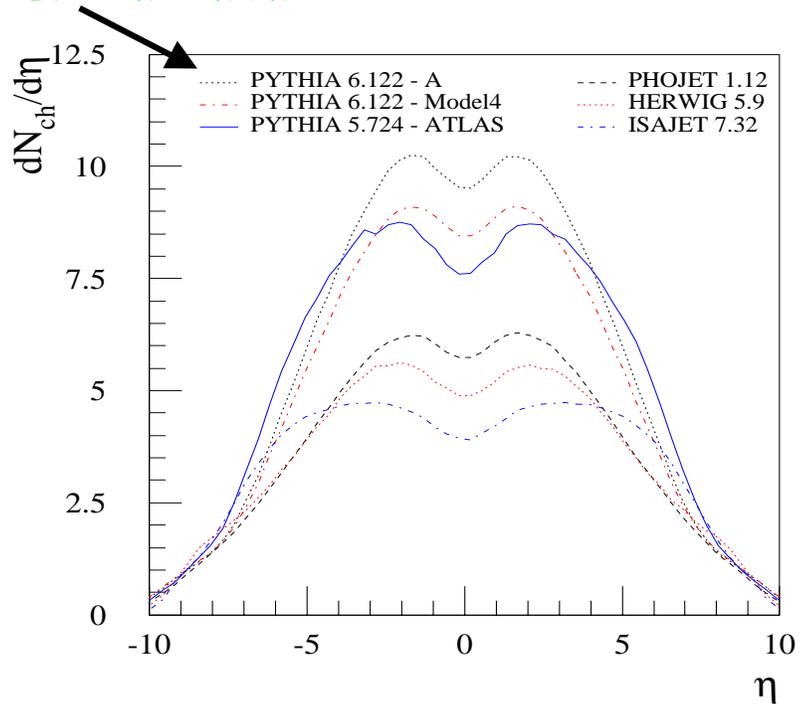




...and the Ugly.

- High Luminosity means multiple interactions.
 - At design luminosity, LHC experiments will face roughly 25 minimum bias events per bunch crossing
- Parton distributions mean no beam energy constraint
 - conservation in the transverse plane
- Initial state radiation (QCD)
 - even more activity

Charged particle versus pseudorapidity in LHC minimum bias events



p_T distribution of Charged particles in LHC minimum bias events



A Slow Start

"The ISR missed the J/ψ and later missed the Υ "
- Maurice Jacob at the last meeting of the ISR committee, January 27, 1984*

"...it took a long time to overcome two major difficulties of collider physics. The first... the relatively low luminosity... The second...the very wide angle spread over which particularly interesting events, such as lepton pair events, may occur... The answer is, of course, sophisticated detectors covering at least the whole central region ($45^\circ < \theta < 135^\circ$) and full azimuth."

- " ...they stumbled on an unexpectedly strong hadron yield; large- p_T production had been discovered, a witness, as we now know, to the pointlike structure within hadrons.
- Early ISR experiments were not prepared for the J/ψ and later ones were too late for the Υ . They nevertheless learned a lot and paved the way.

*Maurice Jacob, Kjell Johnsen, "A Review of Accelerator and Particle Physics at the CERN ISR", CERN 84-13, (30 November, 1984)

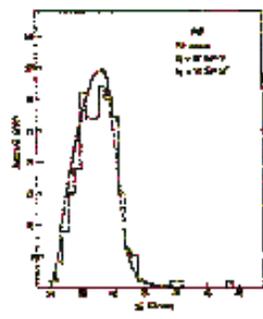
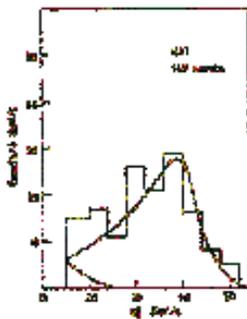
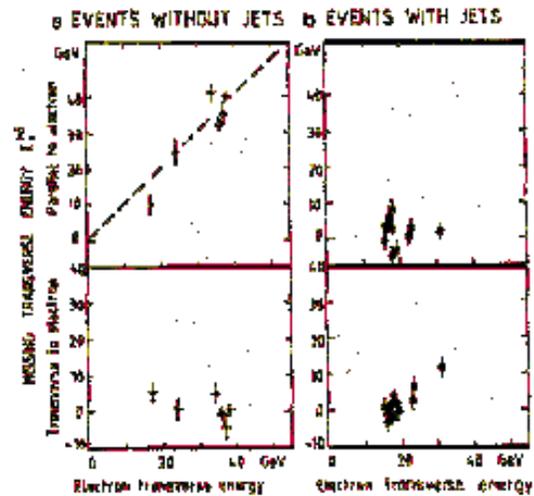


SPS: W Discovery

UA1 and UA2 were well-prepared and right on time.

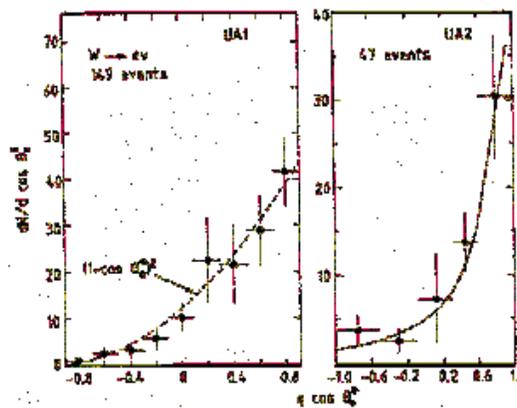
The W cross-section was $\sim 10^{-8} \sigma_{\text{tot}}$

And the W was there at the expected rendez-vous time



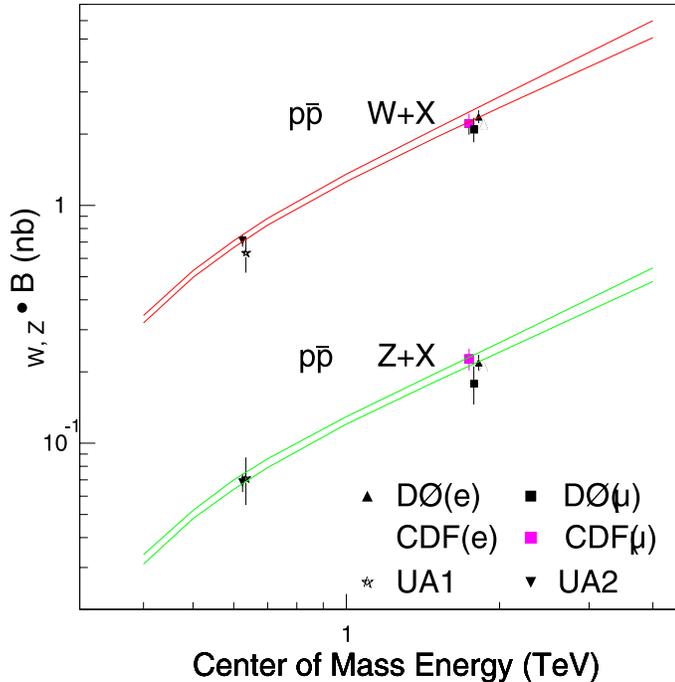
and mass

with the correct spin

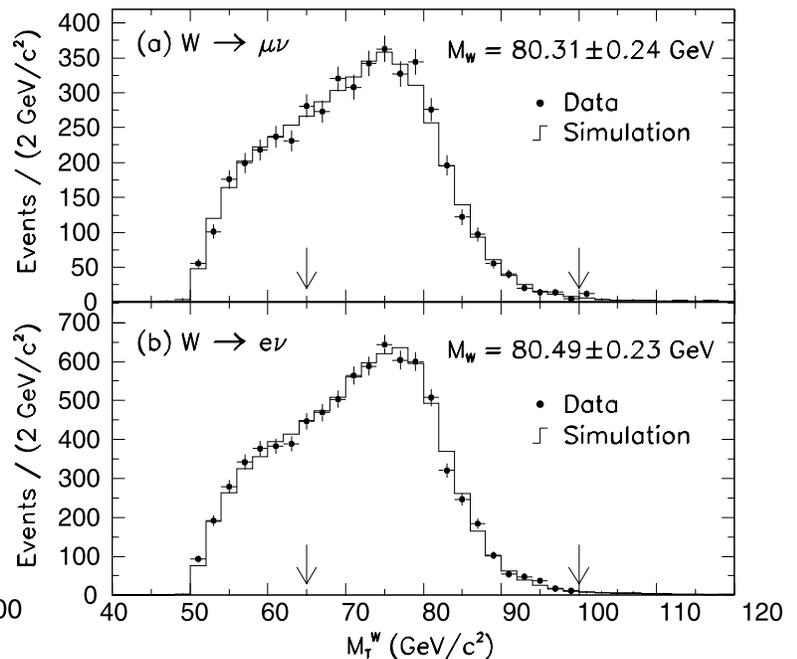
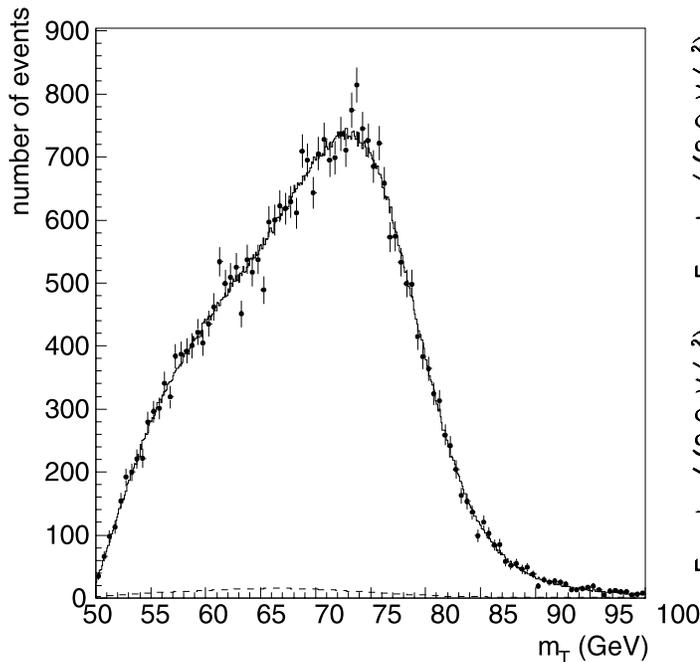




Tevatron M_W



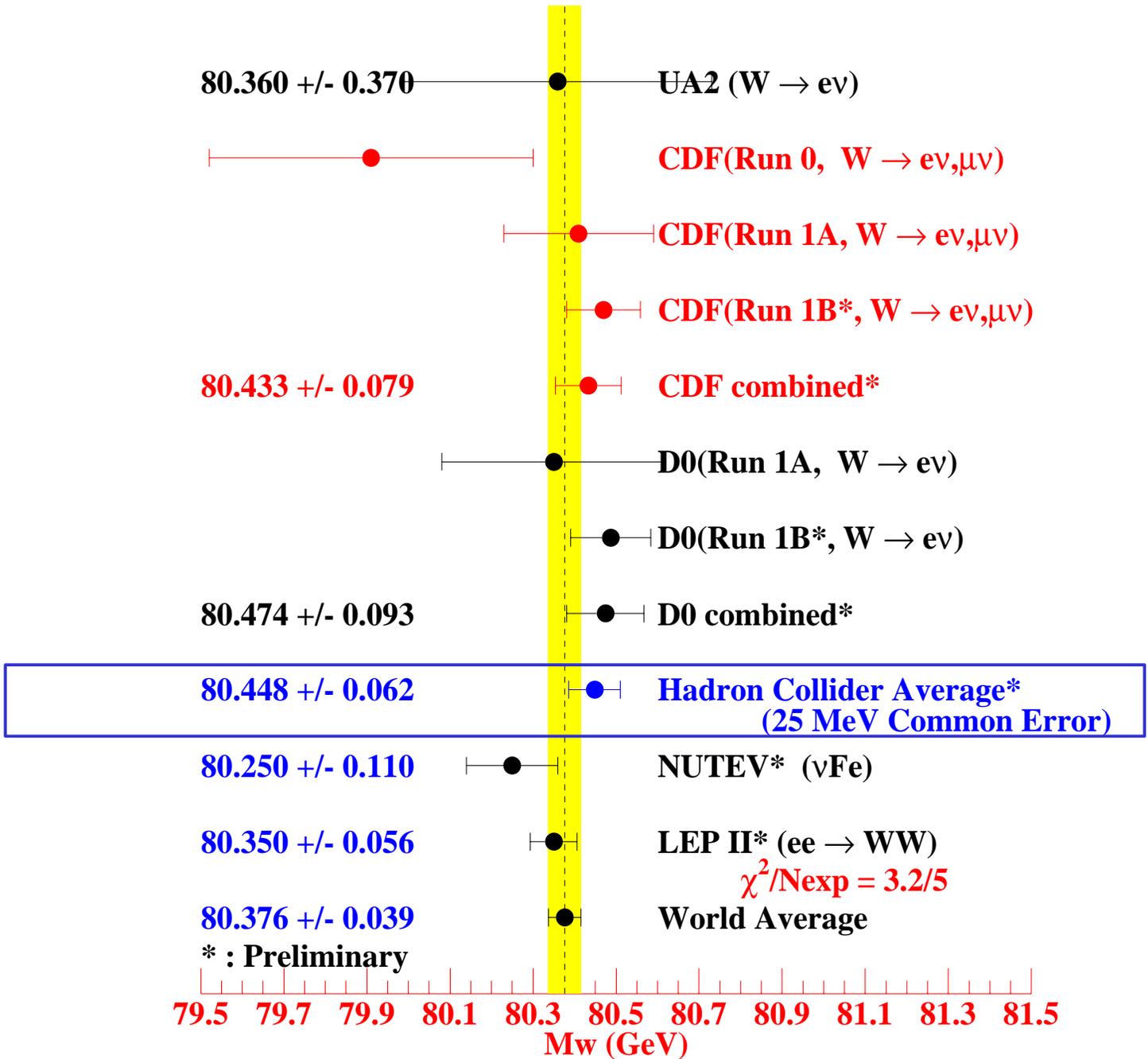
- Higher production cross sections at higher energy:
 - 33k W's DØ
- Momentum calibration from J/ψ , Υ , and Z
 - $M(J/\psi) = 3096.2 \pm 1.5$ MeV
 - $M(\text{CDF})/M(\text{PDG}) \sim 0.99977$





W Mass

- UA2, CDF, DØ \Rightarrow precision masses.

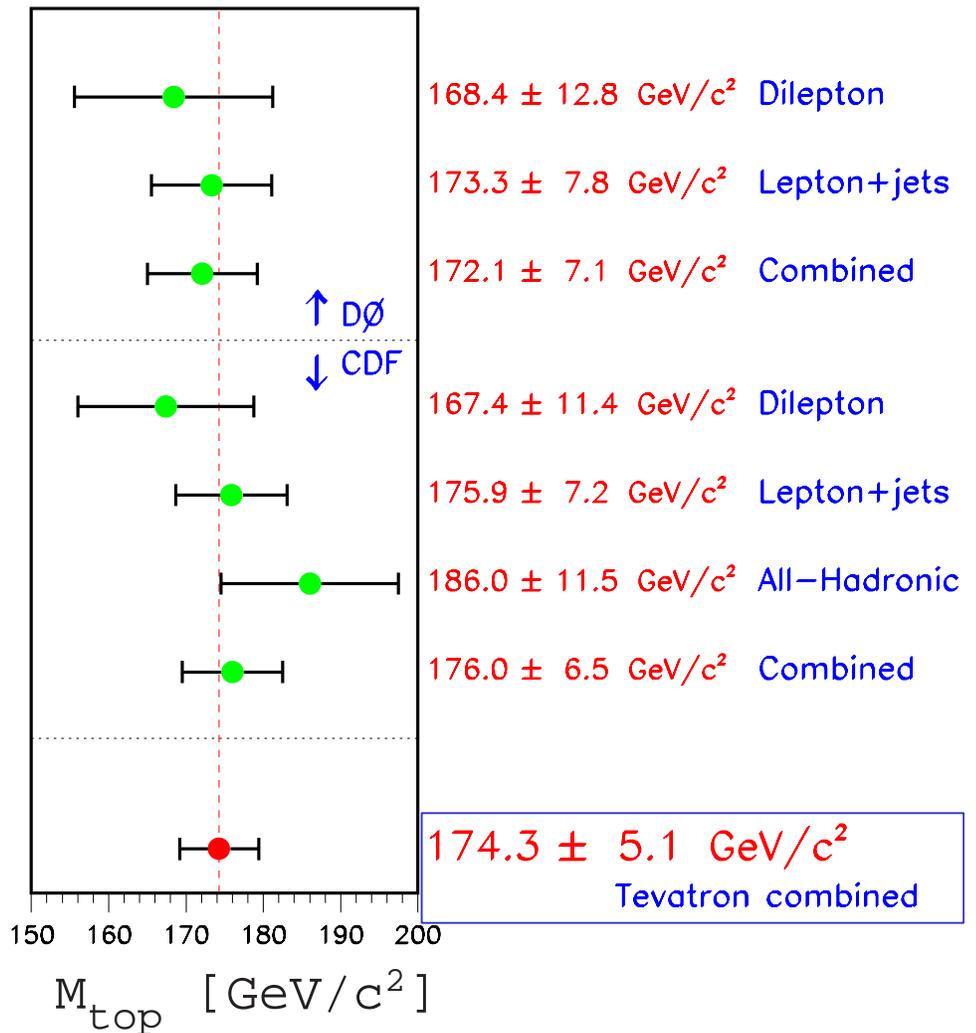
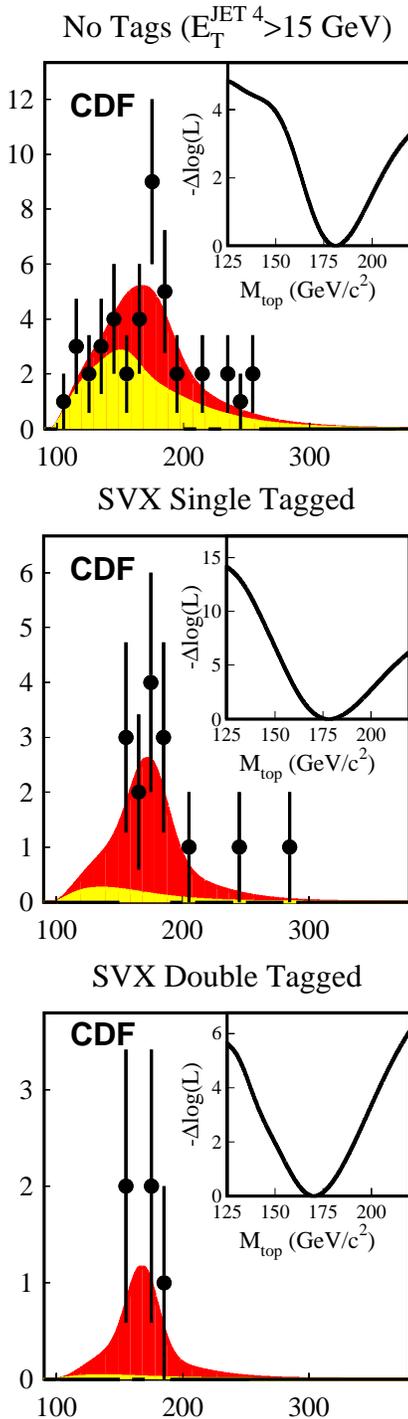




Tevatron: Top Discovery

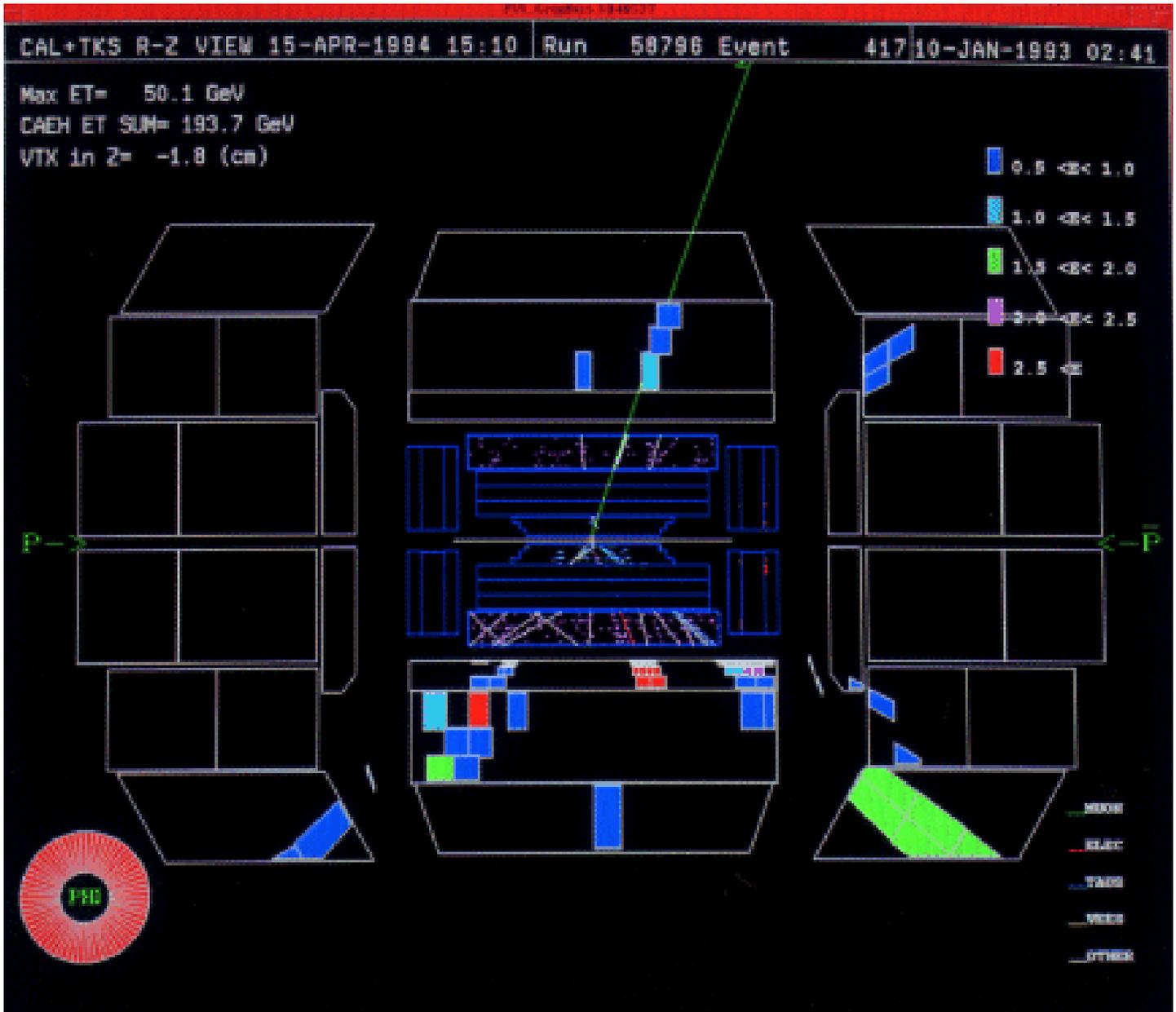
Displaced Vertex b tagging

- CDF and DØ successfully found the top quark with a cross section of $\sim 10^{-10} \sigma_{\text{tot}}$: exceeding expectations.



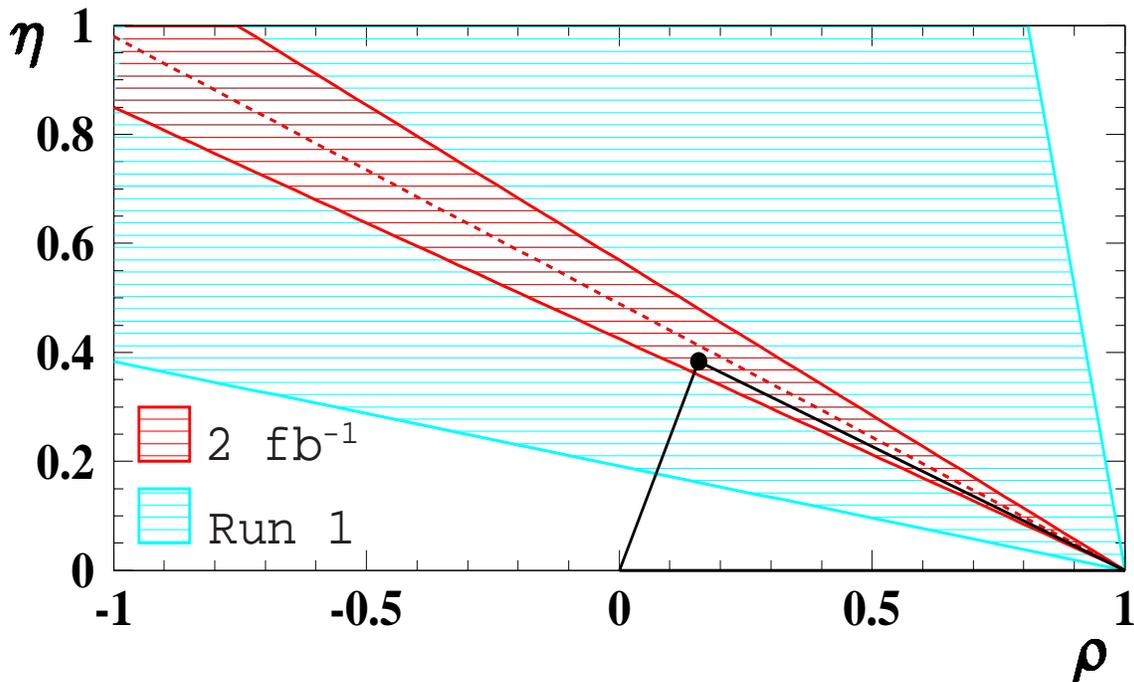


Top Event in DØ





Tevatron: B physics

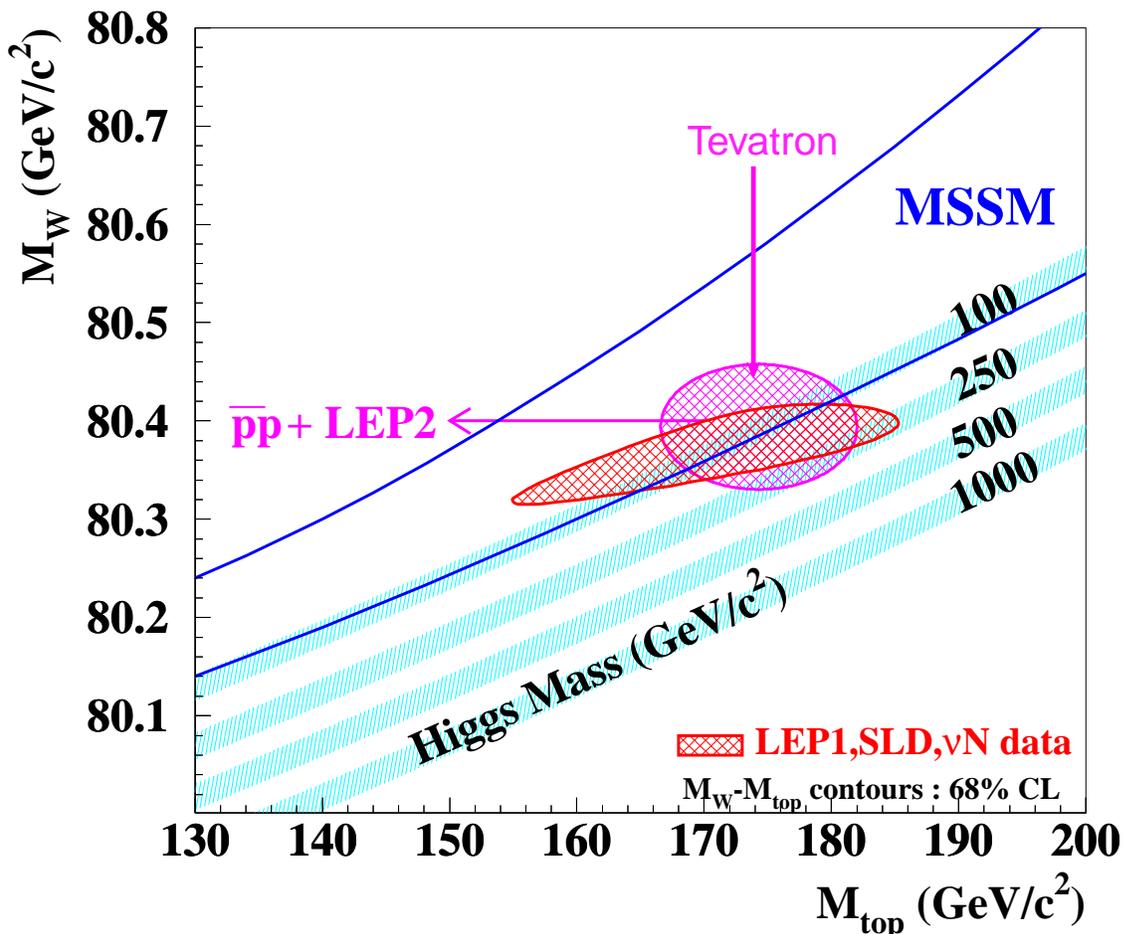


- Precision lifetimes and masses
 - $\tau(B^+)/\tau(B^0) = 1.04 \pm 0.06$
- Flavor tagging: same-side & opposite-side jet
- B_d mixing
- B_c discovery
- First hint of CP violation
 - $\sin(2\beta) \sim 0.8 \pm 0.4$



What's Next ?

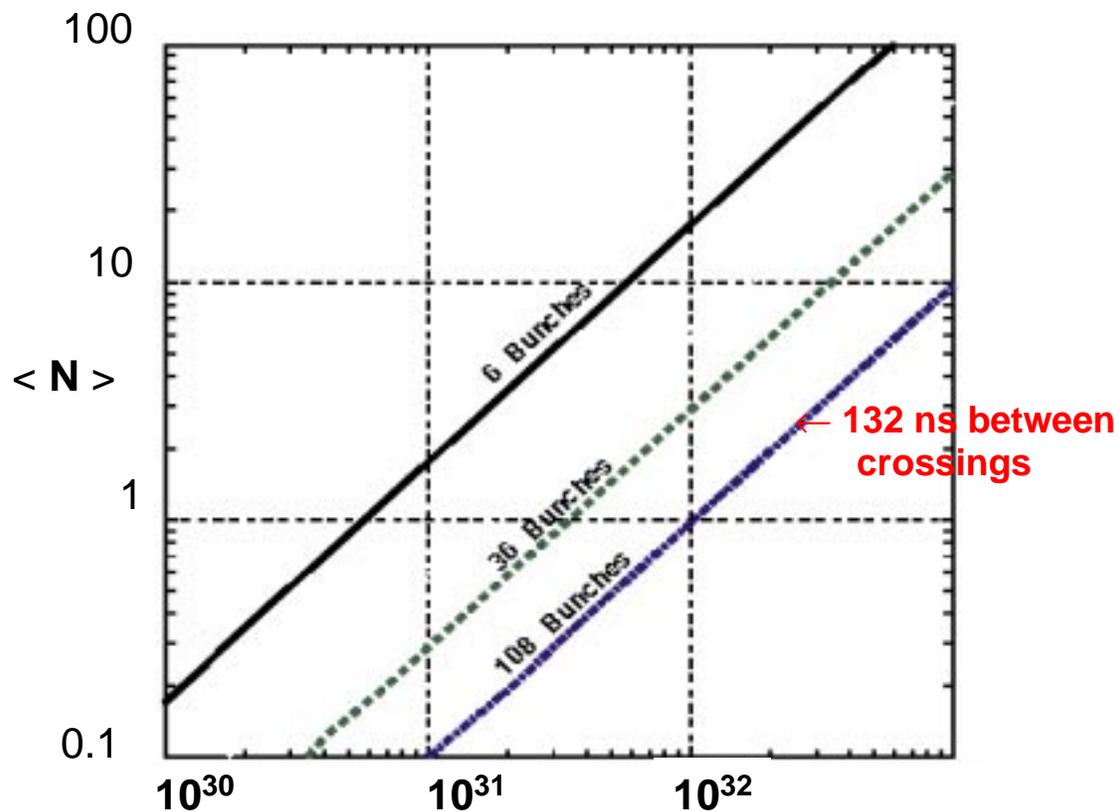
- Experiments all have similar objectives
 - SM data or SUSY \Rightarrow Light higgs
 - SUSY partners
 - Precision electroweak measurements
 - M_W, M_{top}
 - B Physics
 - CKM and CP Violation
 - B_s mixing





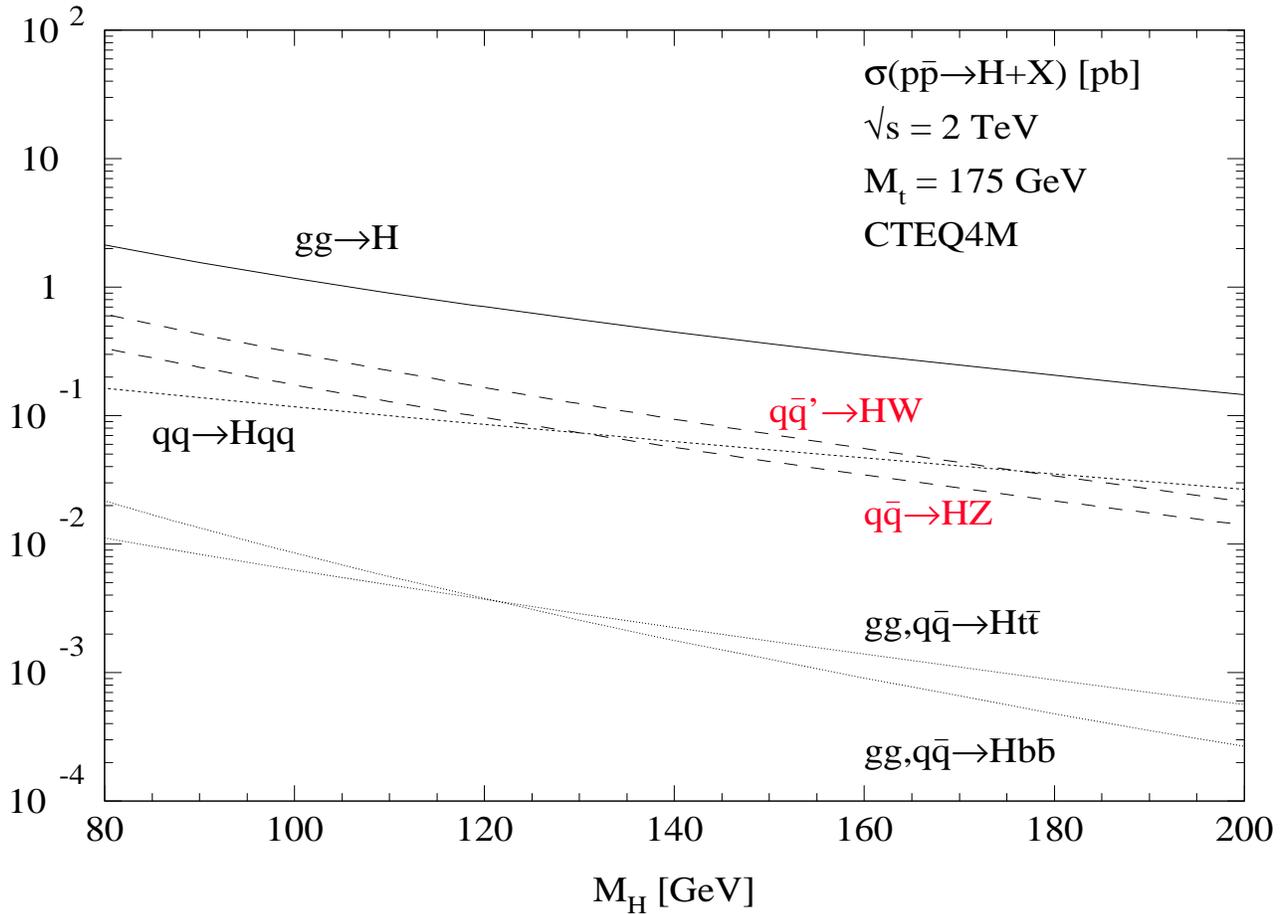
Tevatron Run 2

- Accelerator → Main injector upgrade → 2 TeV
 - 2001 Low luminosity (Run 2a) → 2 fb⁻¹/expt.
 - 0.5 - 2 × 10³² cm⁻² s⁻¹
 - 396 ns → 132 ns bunch crossing
 - $\sigma_z \sim 30$ cm, $\sigma_x \sim 20$ μm
 - 1-6 interactions per crossing
 - 2003 High luminosity (Run 2b) → 15 fb⁻¹/expt.
 - 2.0-5.0 × 10³² cm⁻² s⁻¹
 - 132 ns bunch crossing
 - $\sigma_z \sim 10$ -15 cm ?, $\sigma_{x,y} \sim 20$ μm
 - 2-5 interactions per crossing





Tevatron: SM Higgs Production

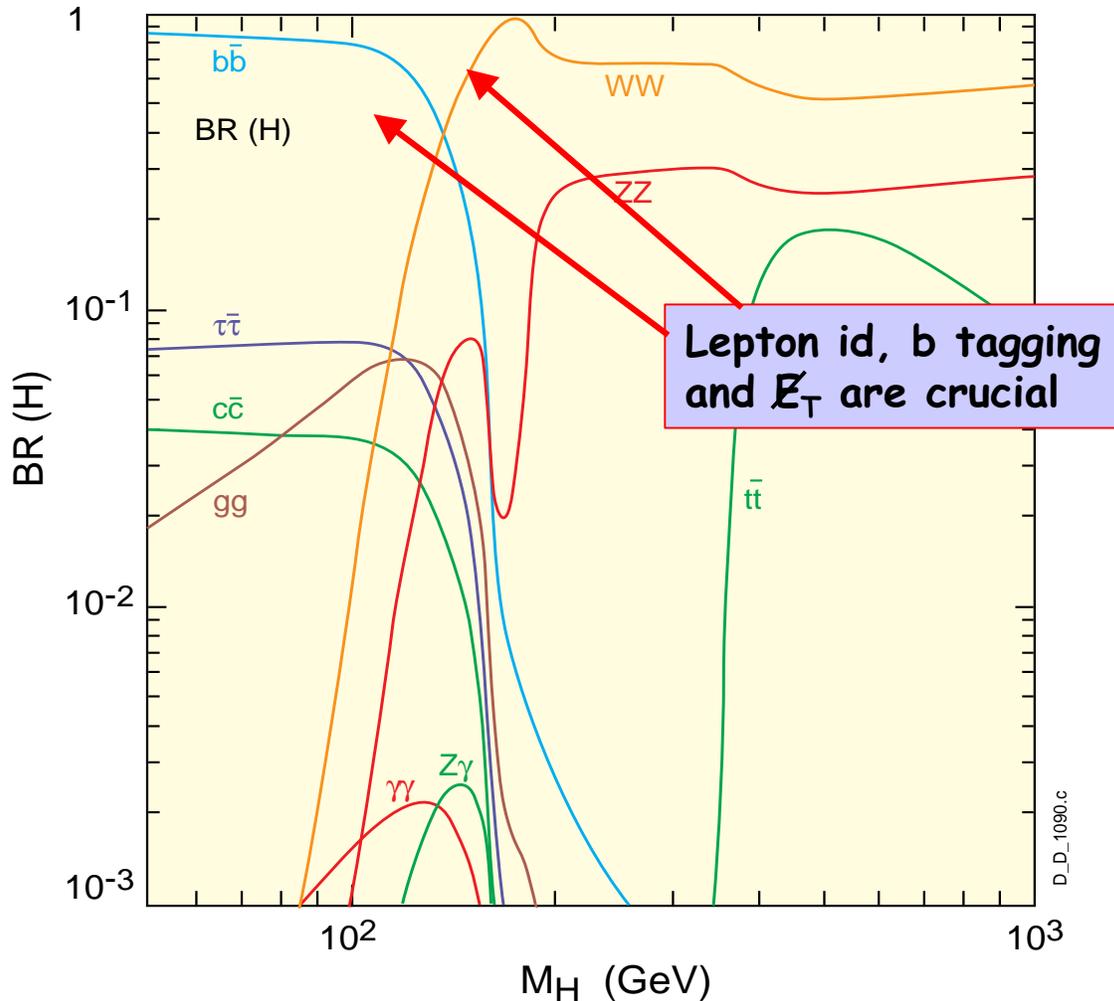


- $gg \rightarrow H$ dominates but swamped by dijets
- $qq' \rightarrow HV$ factor 5-10 lower but backgrounds are more rare ($t\bar{t}, Wbb, Zbb, WZ$)



Tevatron: SM Higgs Decays

A. Djouadi, J. Kalinowski, M. Spira

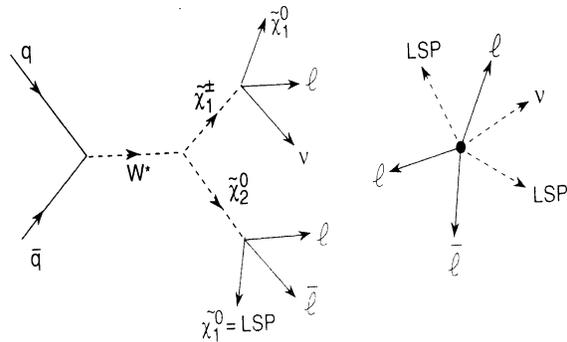
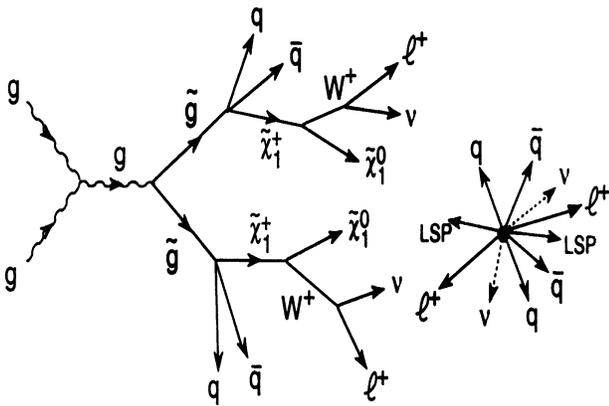


- $m_H < 130$: $H \rightarrow b\bar{b}$ dominant:
 $\Rightarrow W(l\nu, qq')b\bar{b}, Z(\nu\nu, ll, qq)b\bar{b}$ final states
- $m_H > 140$: $H \rightarrow WW$ dominant:
 $\Rightarrow W^+W^-, W^+W^-W^\pm, W^+W^-Z$:
 $l^+l^-\nu\nu, l^+l^-\nu\nu jj, l^+l^-\nu\nu jj$ final states
- MSSM Higgs: many of the same channels as SM and enhanced association to $b\bar{b}$ at large $\tan\beta$

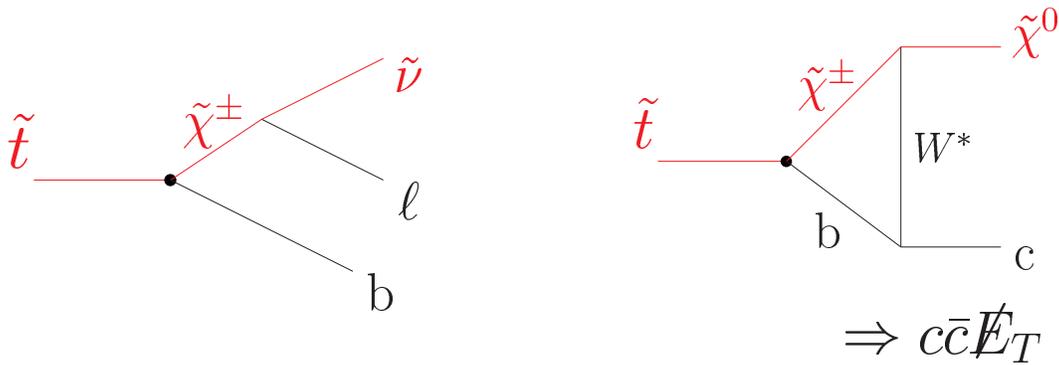


Lepton id, b tagging, \cancel{E}_T

- W mass, Top, B physics
- SUSY searches:
 - gluino pair production with cascade to like sign di-leptons or gauginos to tri-leptons

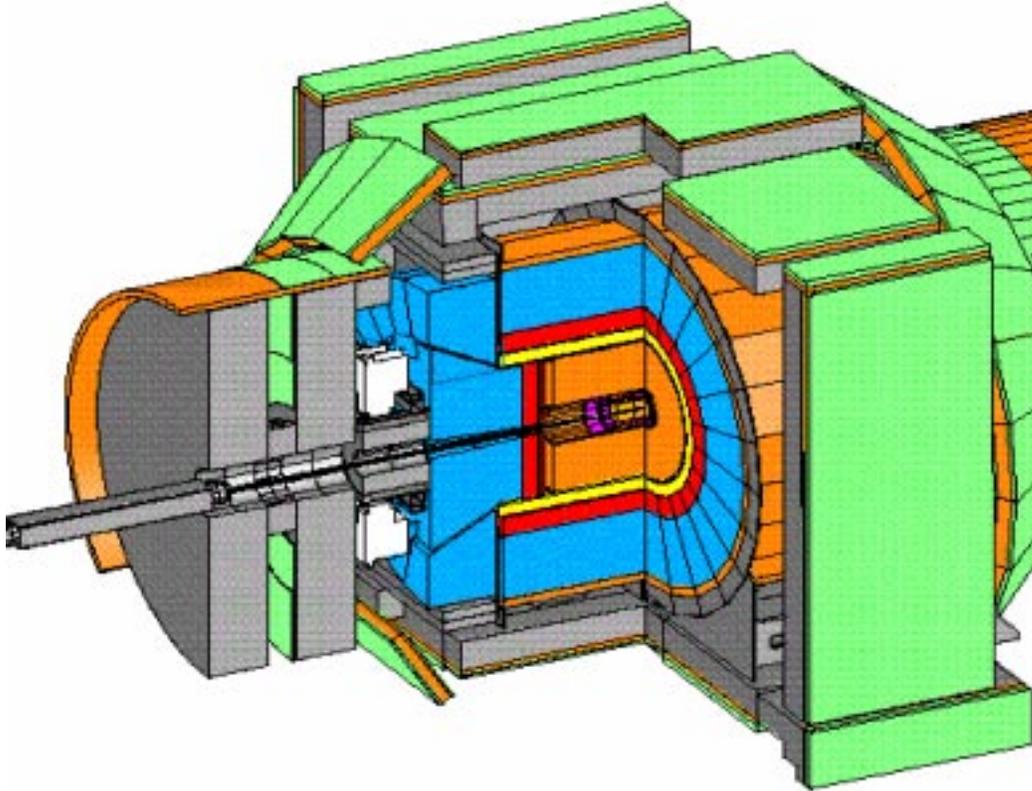


- stop pair production to top-like decays with bottom or cascades to charm





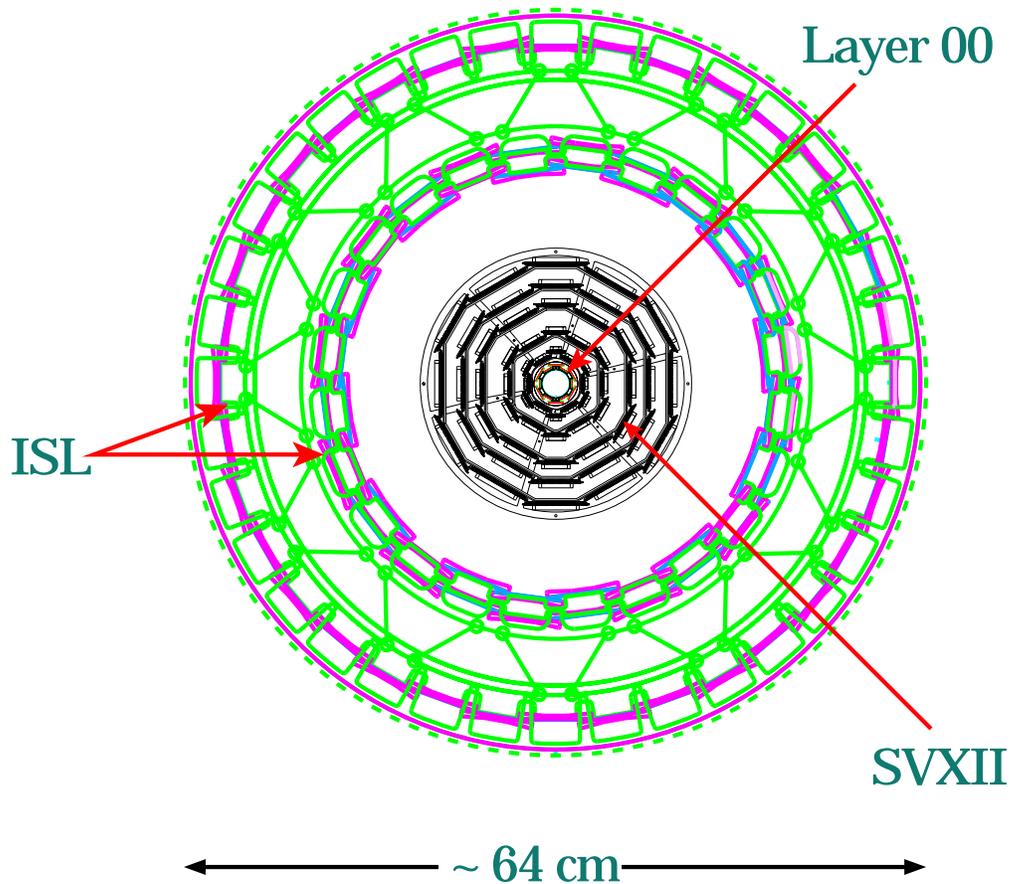
CDF II



- Endplug Calorimeter
- Tracking
 - Silicon Vertex Detector (Layer 00 + SVX II)
 - Intermediate Silicon Layers (ISL)
 - Central Outer Tracker
 - Time of Flight
- Front End Electronics
- Trigger/DAQ (pipelined)
- Extended Muon systems



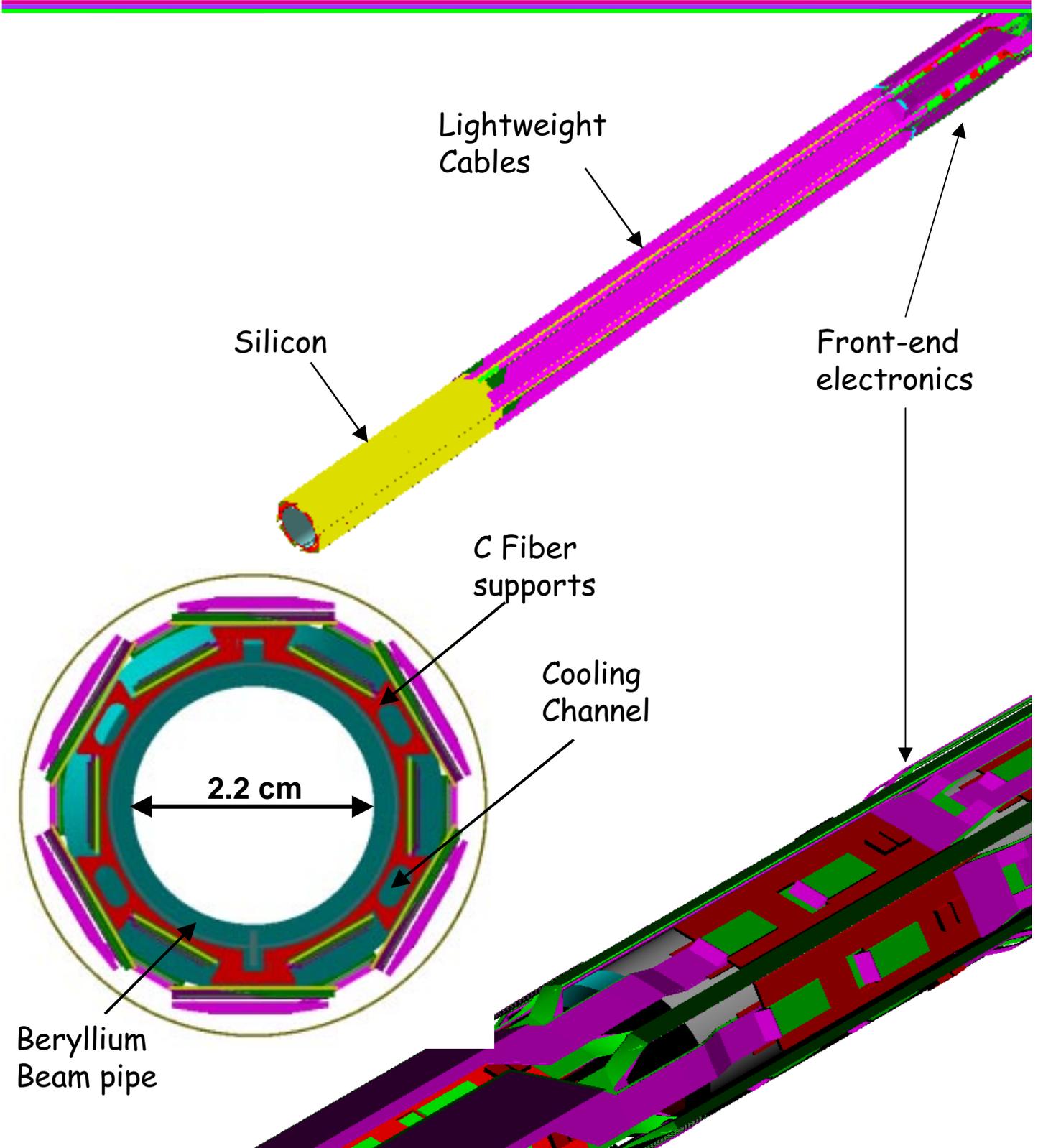
CDF II Silicon



CDF	Layer 00	SVX II	ISL	Totals
Layers	1	5	2	8
Length	0.9 m	0.9 m	1.9 m	
Channels	13824	405504	303104	722432
Modules	48 SS	360 DS	296 DS	704
Readout Length	14.8 cm	14.5 cm	21.5 cm	
Inner Radius	1.35 cm	2.5 cm	20 cm	1.35 cm
Outer Radius	1.65 cm	10.6 cm	28 cm	28 cm
Power	~100 W	1.4 kW	1.0 kW	2.5 kW

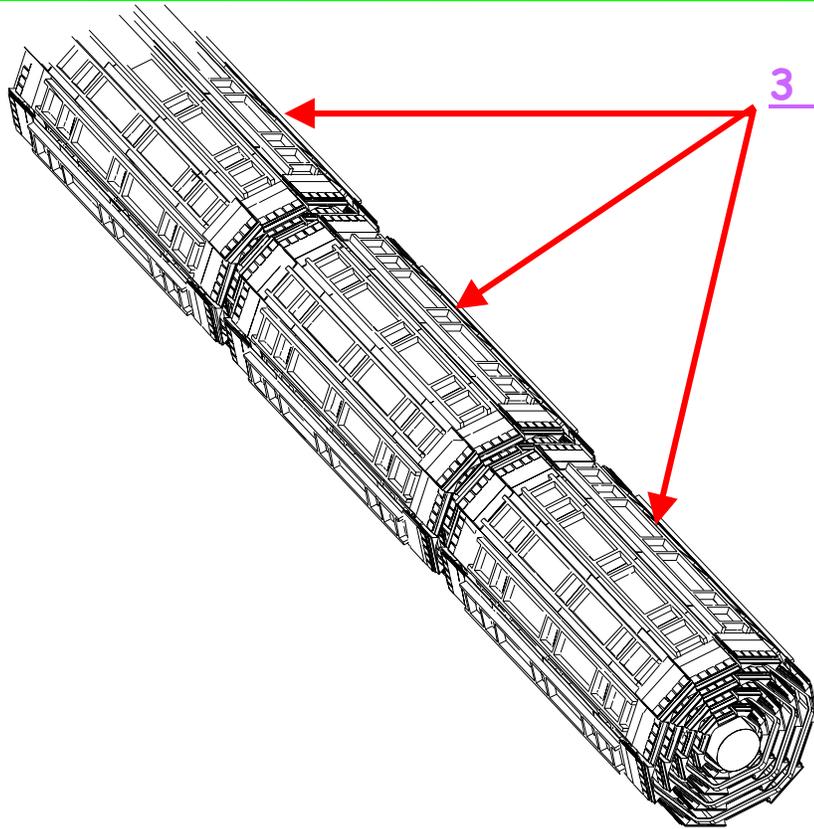


CDF II Layer 00



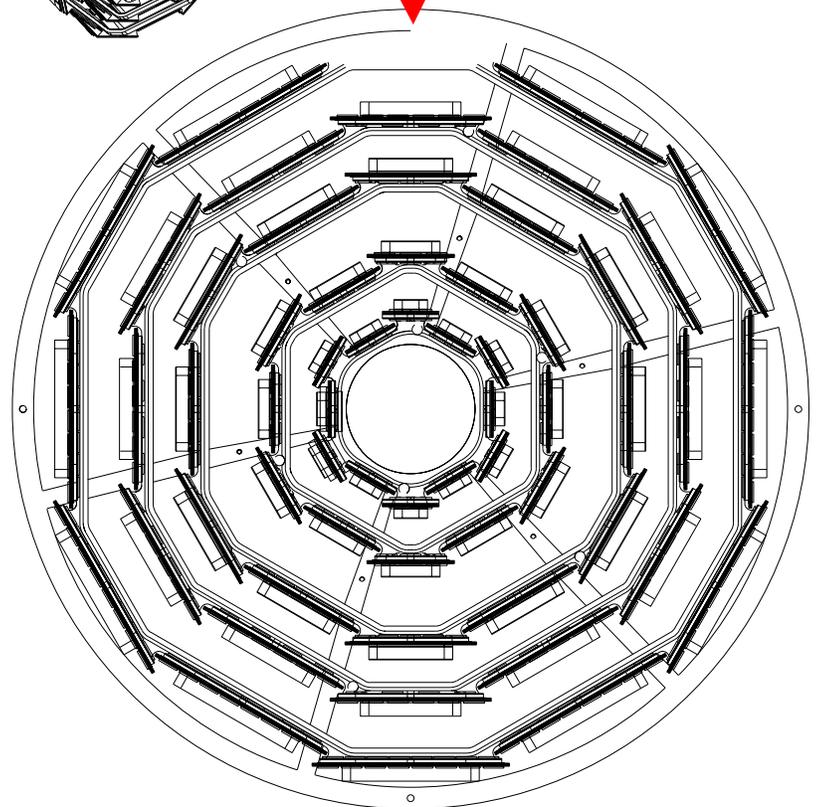


CDF SVX II



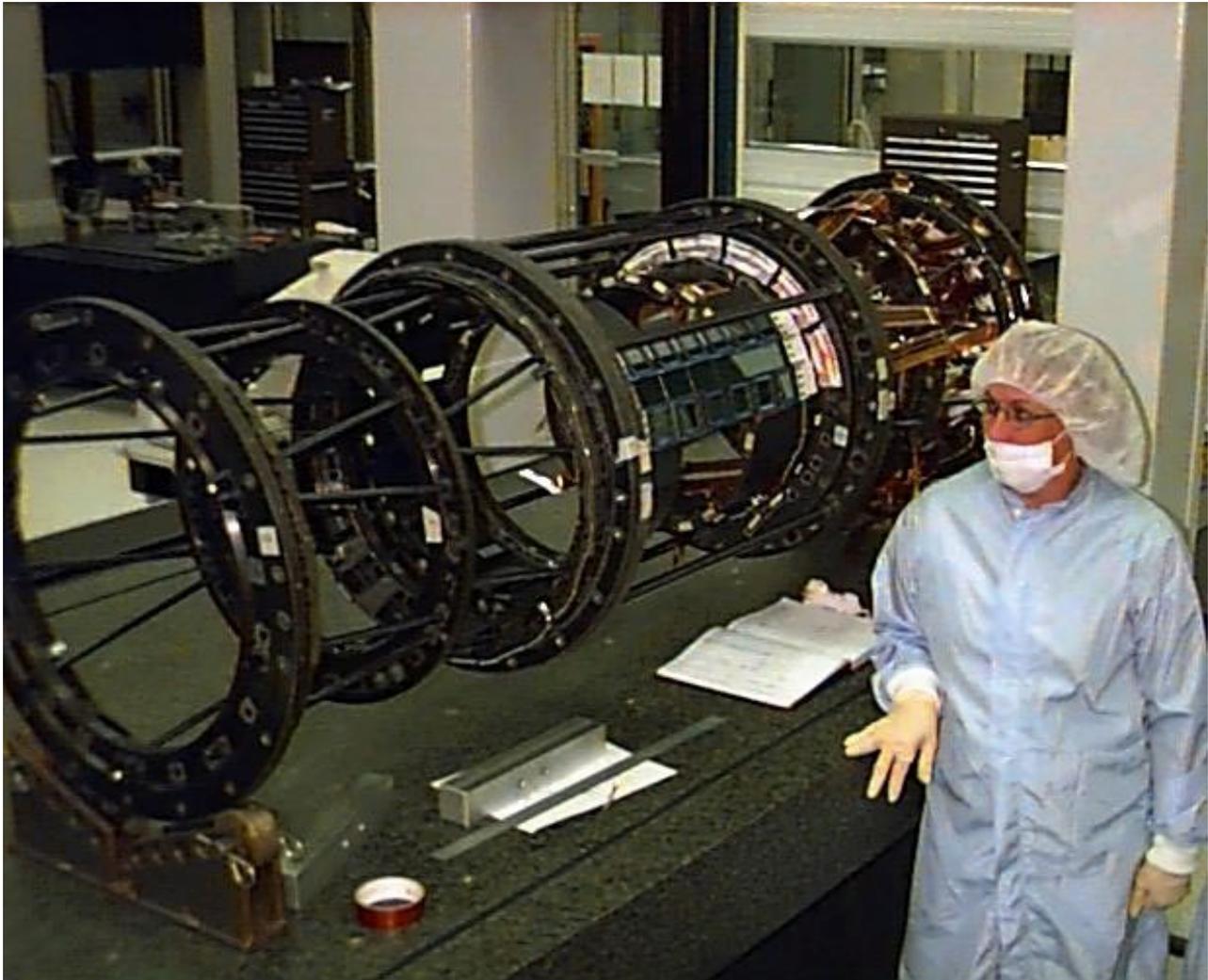
3 Barrels: Compact design:

- Electronics mounted directly on silicon to avoid longitudinal gaps.
- Overlaps in ϕ
- Radial span ~ 8 cm for 5 layers !





CDF Intermediate Si Layers

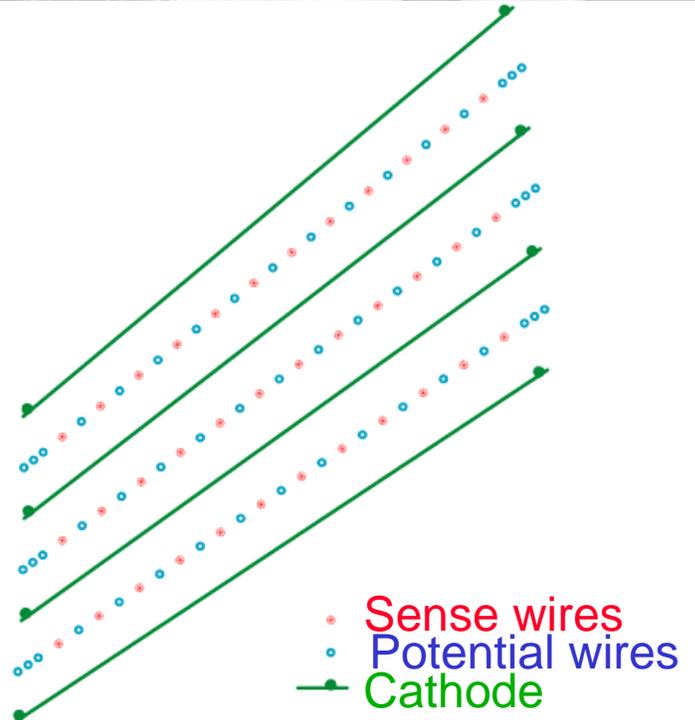




CDF Central Outer Tracker (COT)

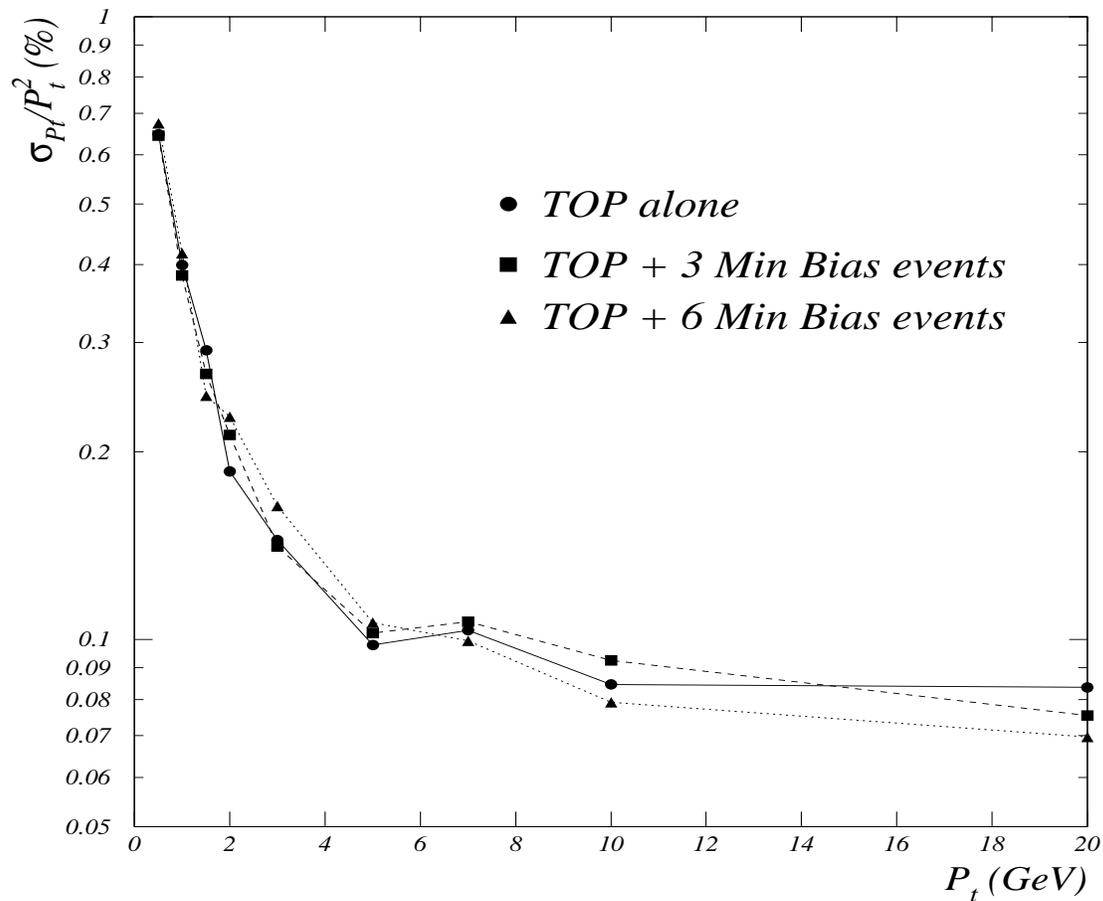


- 96 wire planes
 - (8 superlayers)
 - 50% are 3° stereo
 - Drift trajectories uniform (0.88 cm cell)
 - 30,240 sense wires
- Novel Construction:
 - Use winding machine
 - 29 wires/pc board, precision length





Tracker Performance



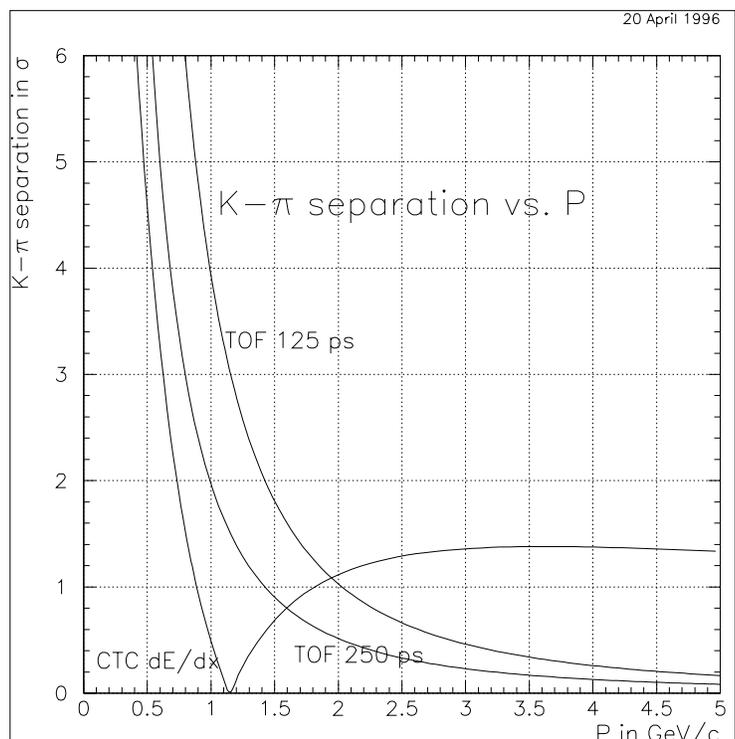
- Improved momentum resolution
 - run 1 $\delta p_T/p_T^2 \sim 0.21\%$
 - run 2 $\delta p_T/p_T^2 < 0.1\%$
- High efficiency & better stereo
- Impact Parameter Resolution
 - $\sigma_d(r\phi) \sim 6 \oplus 20/p_T$ [μm]
 - $\sigma_d(rz) \sim 50$ [μm]



CDF TOF

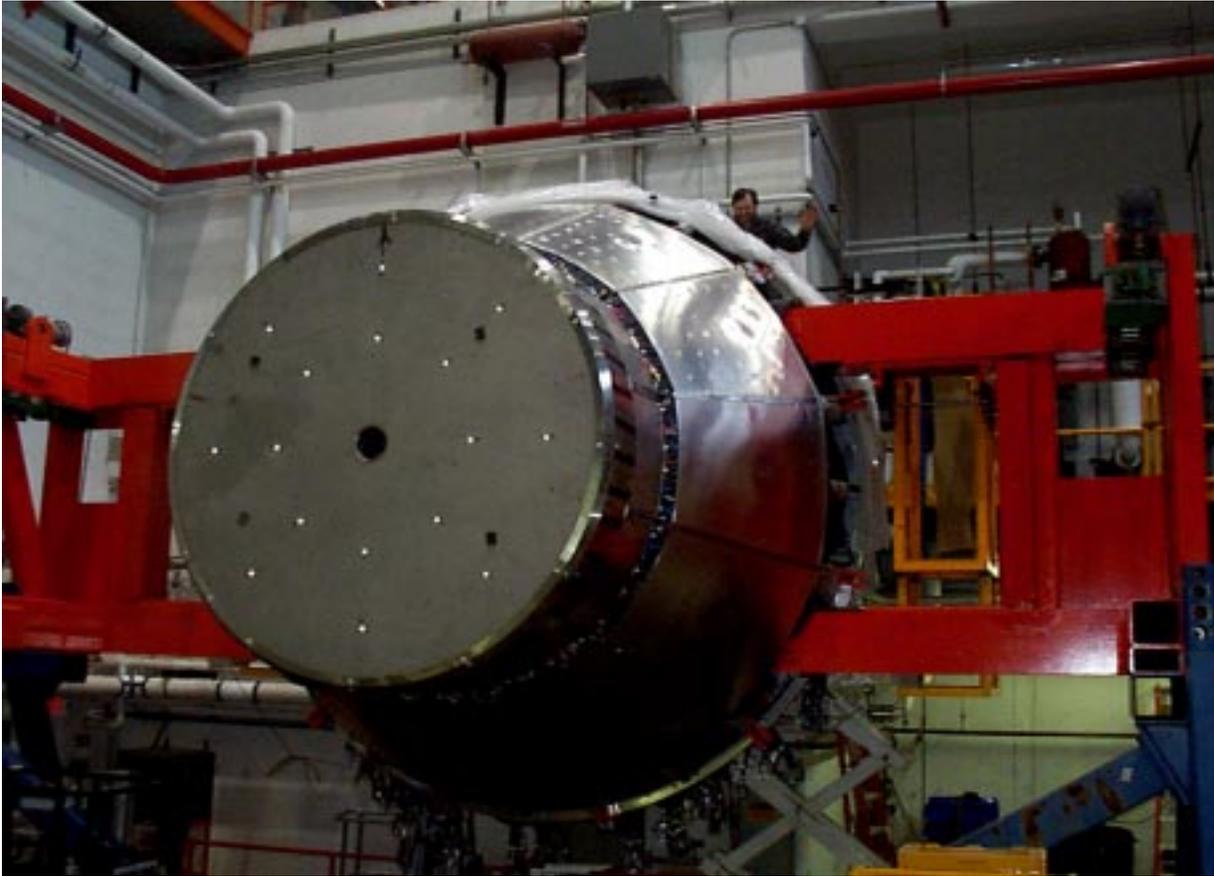


- 216 scintillator bars just outside COT
 - 4x4 cm² by 2.8 m long
 - r/o both ends w/fine-mesh pmt's
 - 100 ps resolution expected
- Primary purpose k id for B flavor tagging





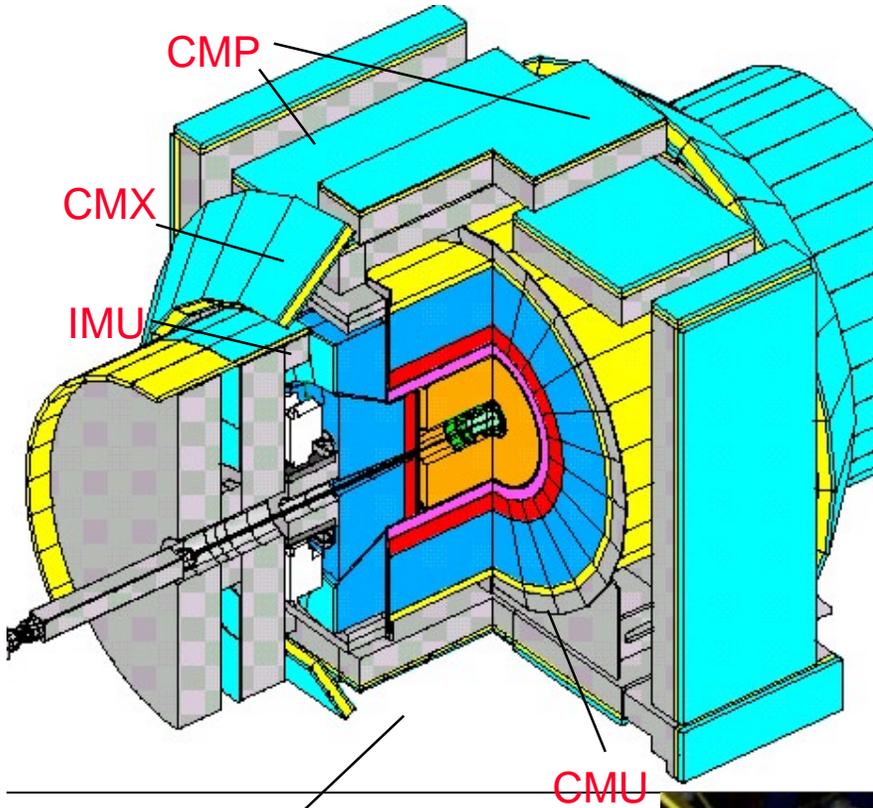
CDF Calorimeters



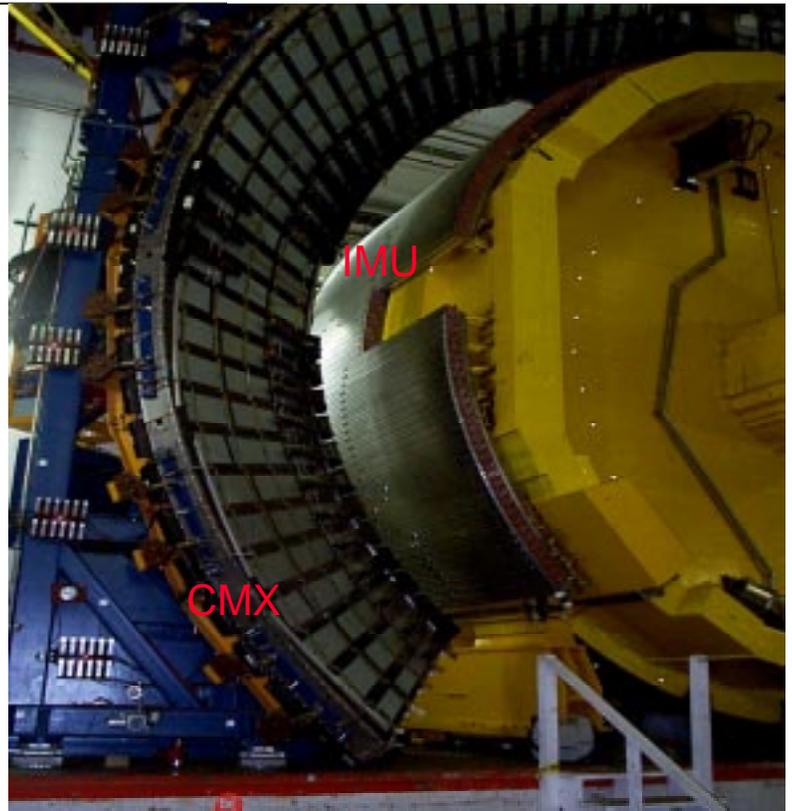
- **New Plug Calorimeters**
 - Scintillator tile design
- **Central Calorimeters Refurbished**
 - new faster electronics



CDF Muon System



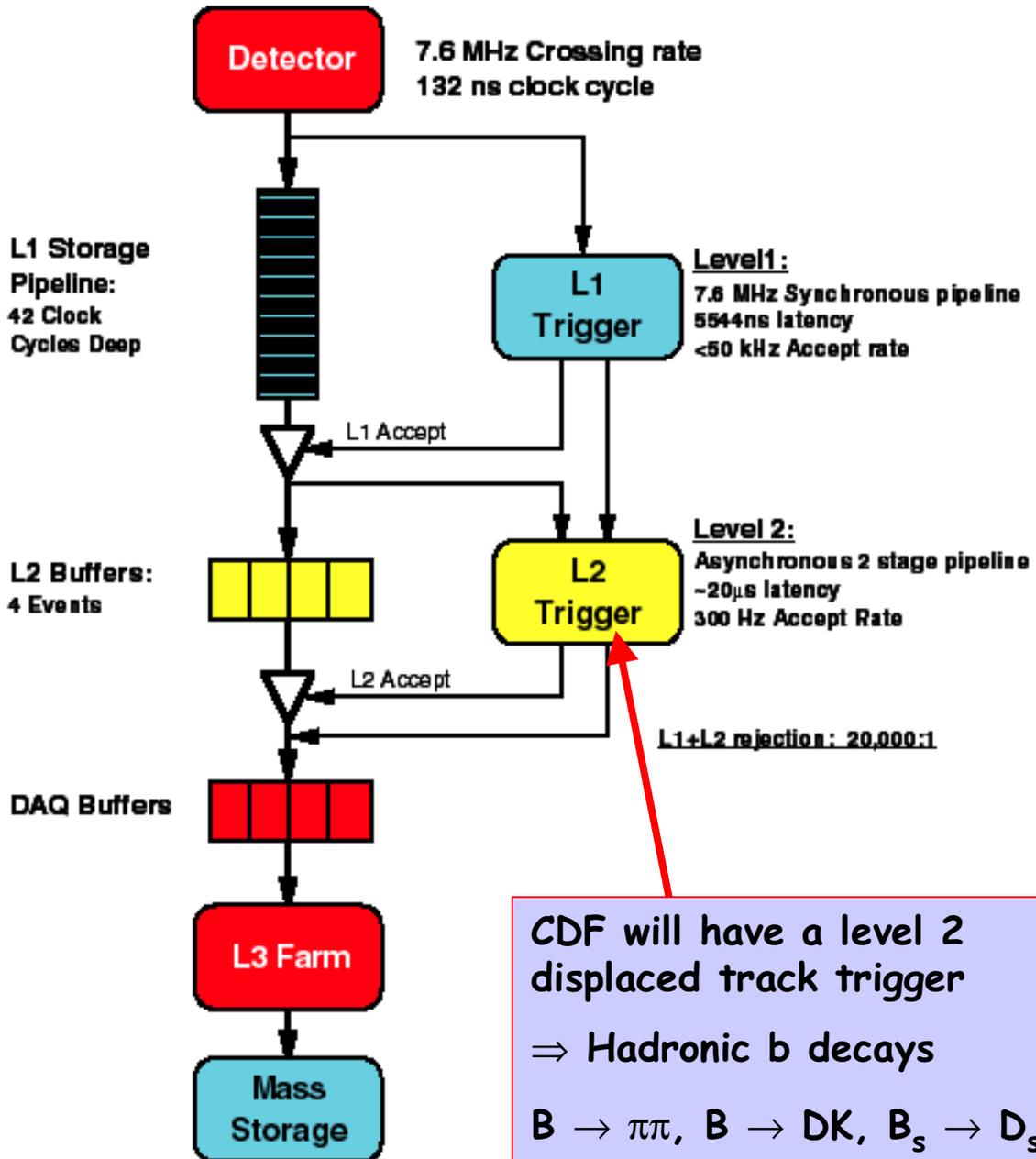
CMX Mini Skirt





CDF Trigger/DAQ

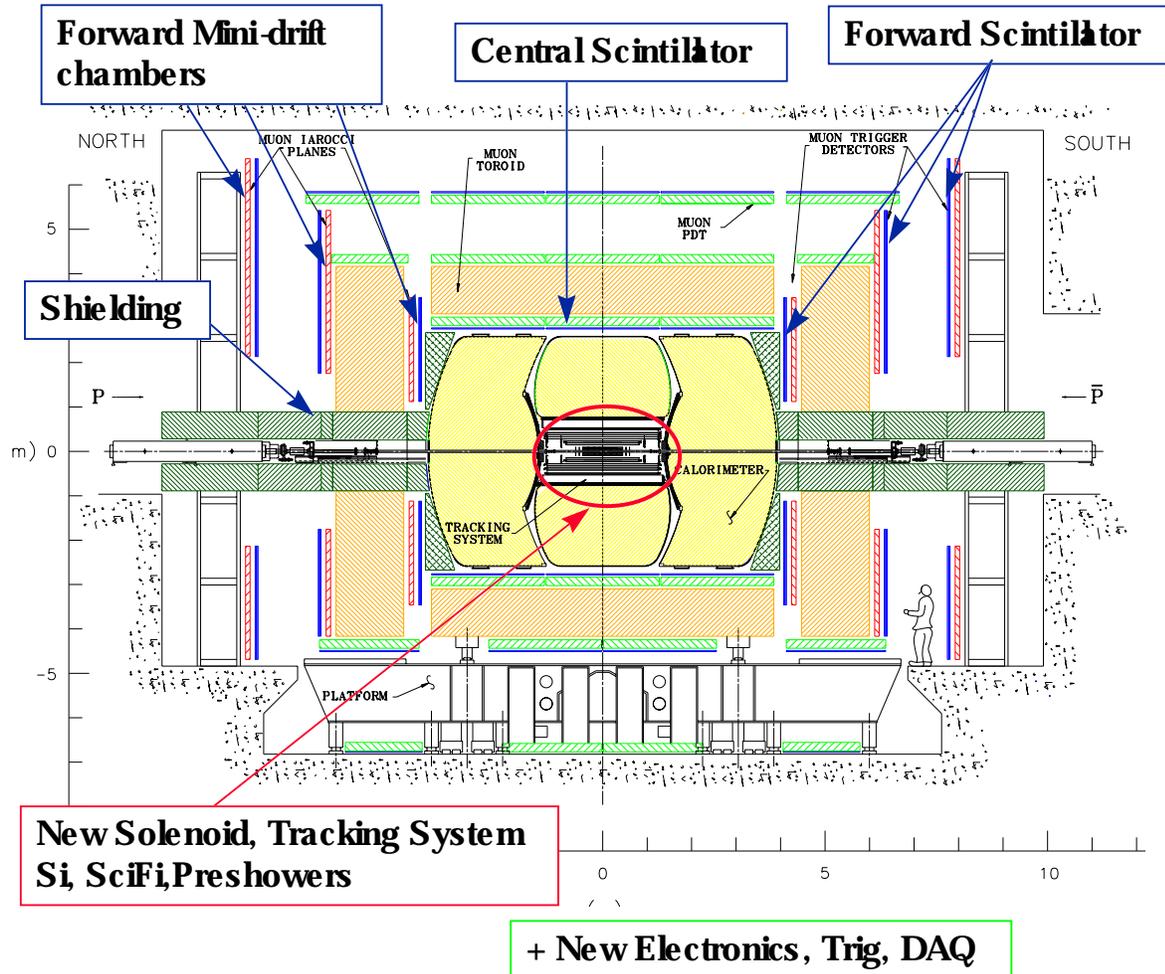
Dataflow of CDF "Deadtimeless" Trigger and DAQ



CDF will have a level 2 displaced track trigger
 ⇒ Hadronic b decays
 $B \rightarrow \pi\pi$, $B \rightarrow DK$, $B_s \rightarrow D_s n\pi$



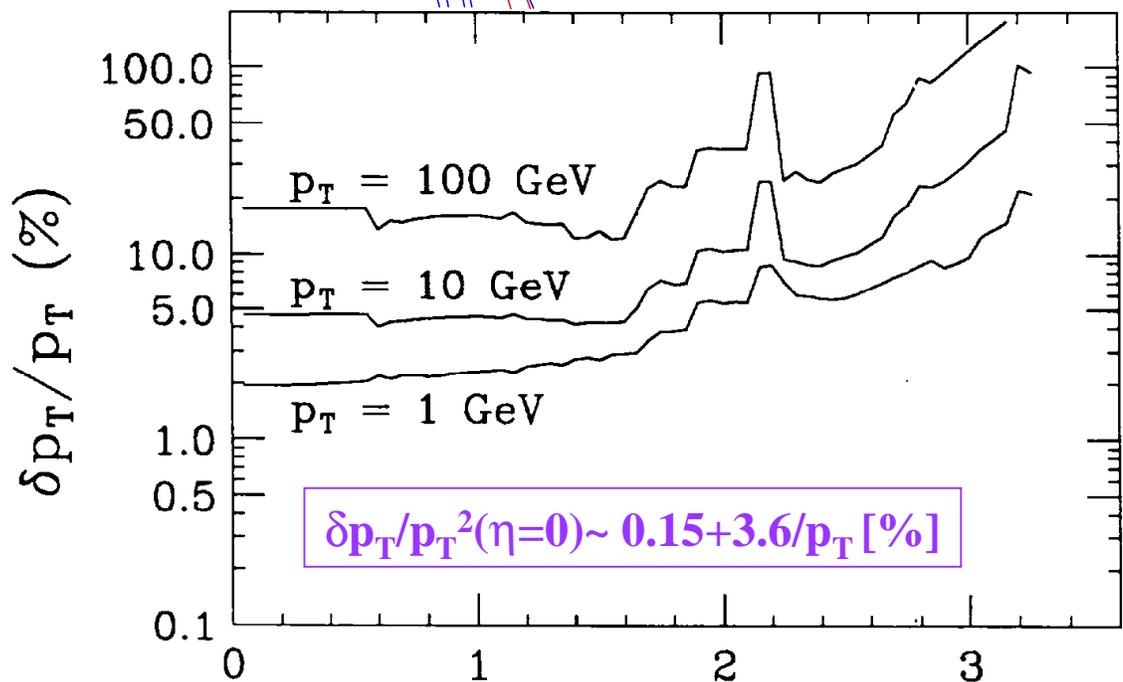
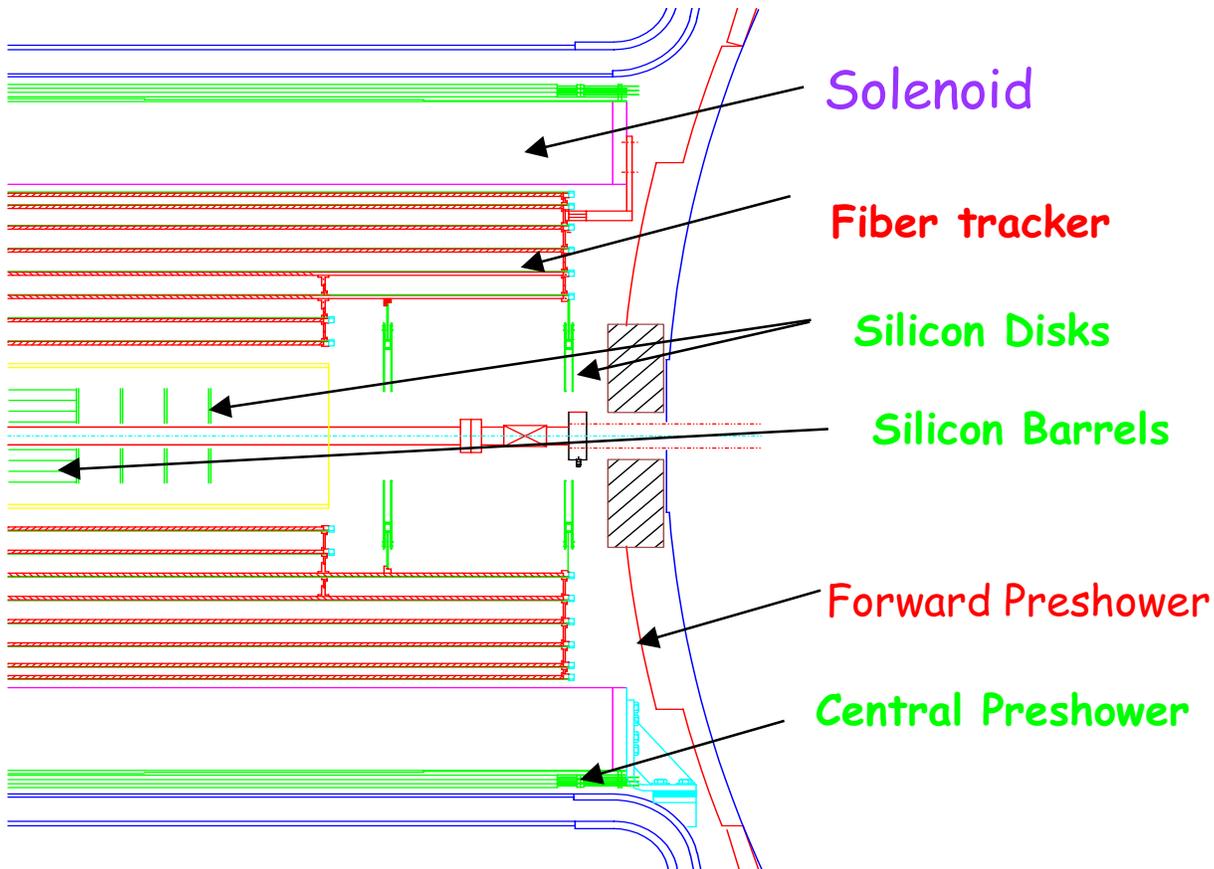
DØ Upgrade



- Silicon Microstrip Vertexer
- Central Fiber Tracker
- 2T Solenoid
- Enhanced Muon System
- Electronics/DAQ/Trigger

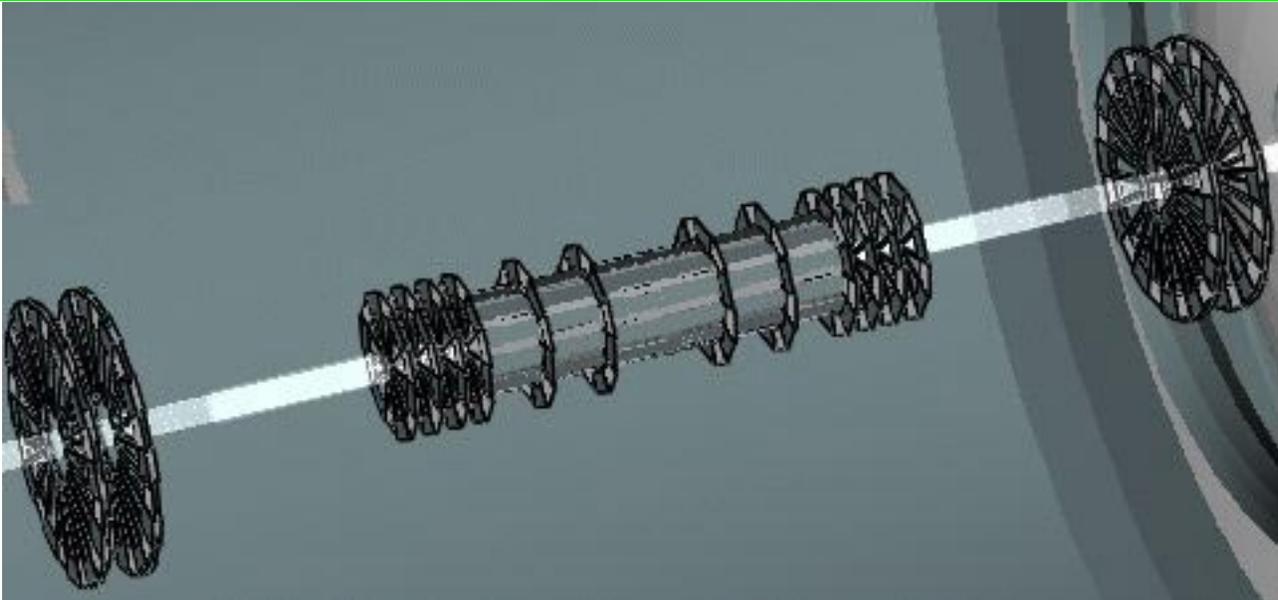


DØ II Tracker





DØ II Silicon



DØ	6 Barrels	F Disks	H Disks	Totals
Layers/planes	4	6/side	2/side	
Δz	77 cm	48 cm	10 cm	
Channels	387120	258000	147456	792576
Modules	432	144	192	768
Readout Length	12 cm	7.5 cm	14.9 cm	
Inner Radius	2.7 cm	2.6 cm	9.5 cm	2.6 cm
Outer Radius	9.4 cm	10.5 cm	26 cm	26 cm

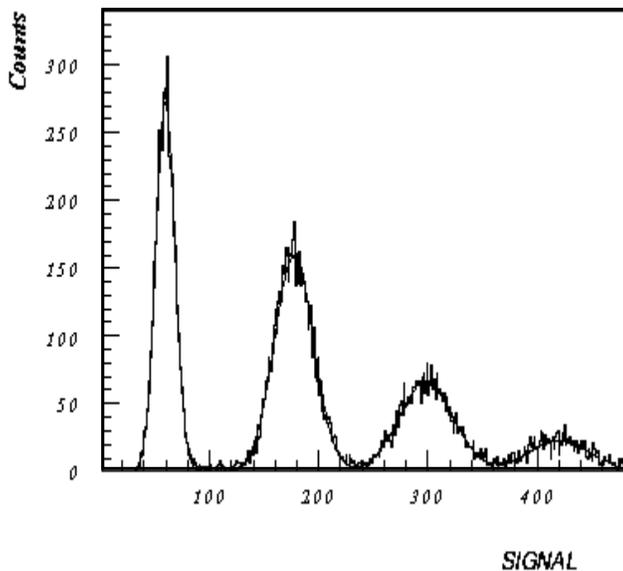
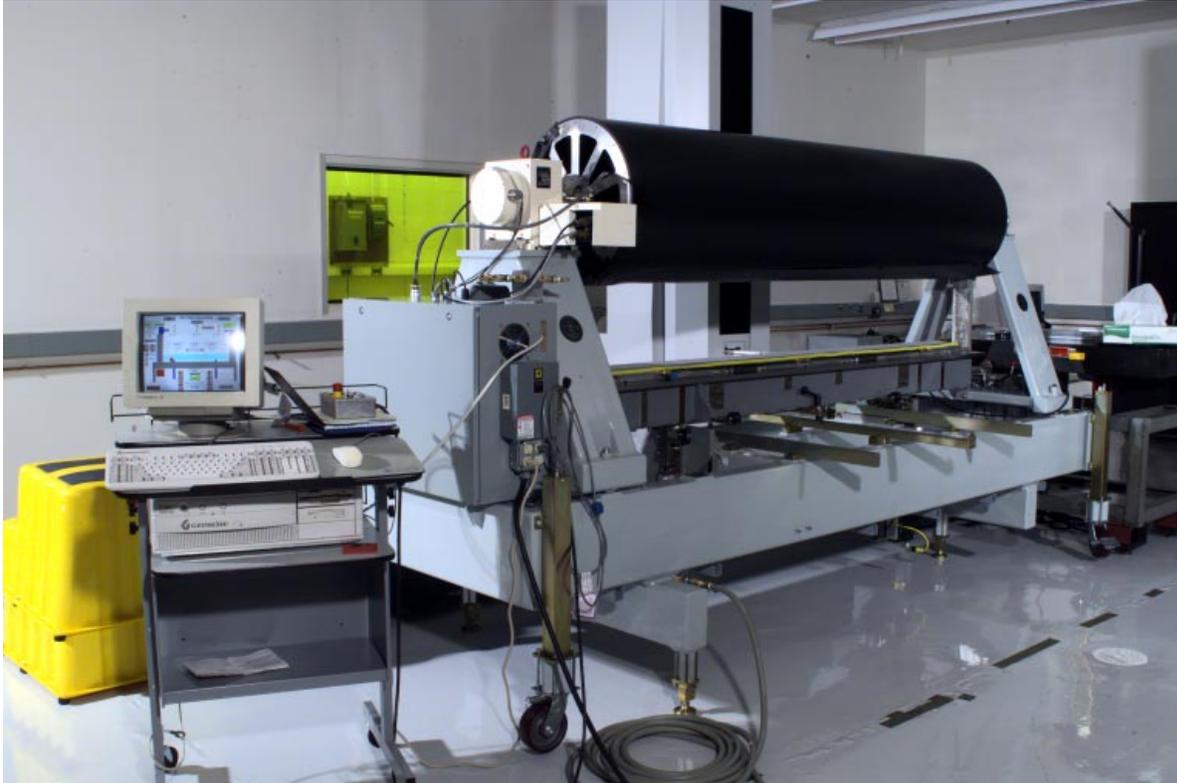
- Impact Parameter Resolution

$$\sigma_d(r\phi) \sim 12 \oplus 35/p_T \text{ } [\mu\text{m}]$$

$$\sigma_d(rz) \sim 40 \text{ } [\mu\text{m}]$$



DØ Fiber Tracker

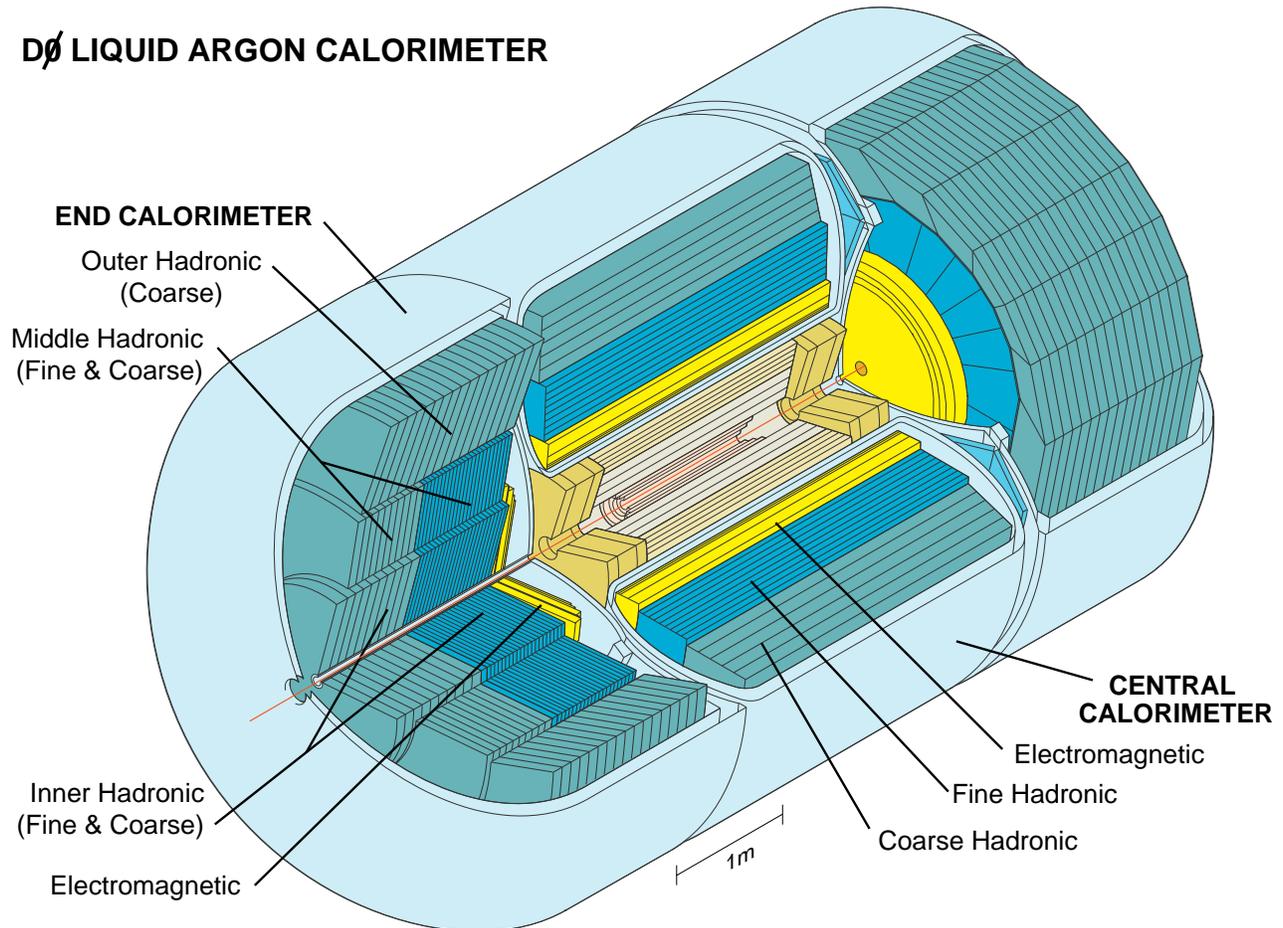


- VLPC @ HISTE VI (Si:As avalanche photodiode)
 - High QE >80%
 - noise occupancy < 0.1 %
 - High Rate capability
 - > 40 MHz
 - High production yield
 - > 70% (27% expected)



DØ Calorimeters

DØ LIQUID ARGON CALORIMETER



$\sigma(E)/E \sim 15\%/\sqrt{E}$ for electrons

$\sigma(E)/E \sim 50\%/\sqrt{E}$ for pions

$e/\pi \leq 1.05$ above 30 GeV

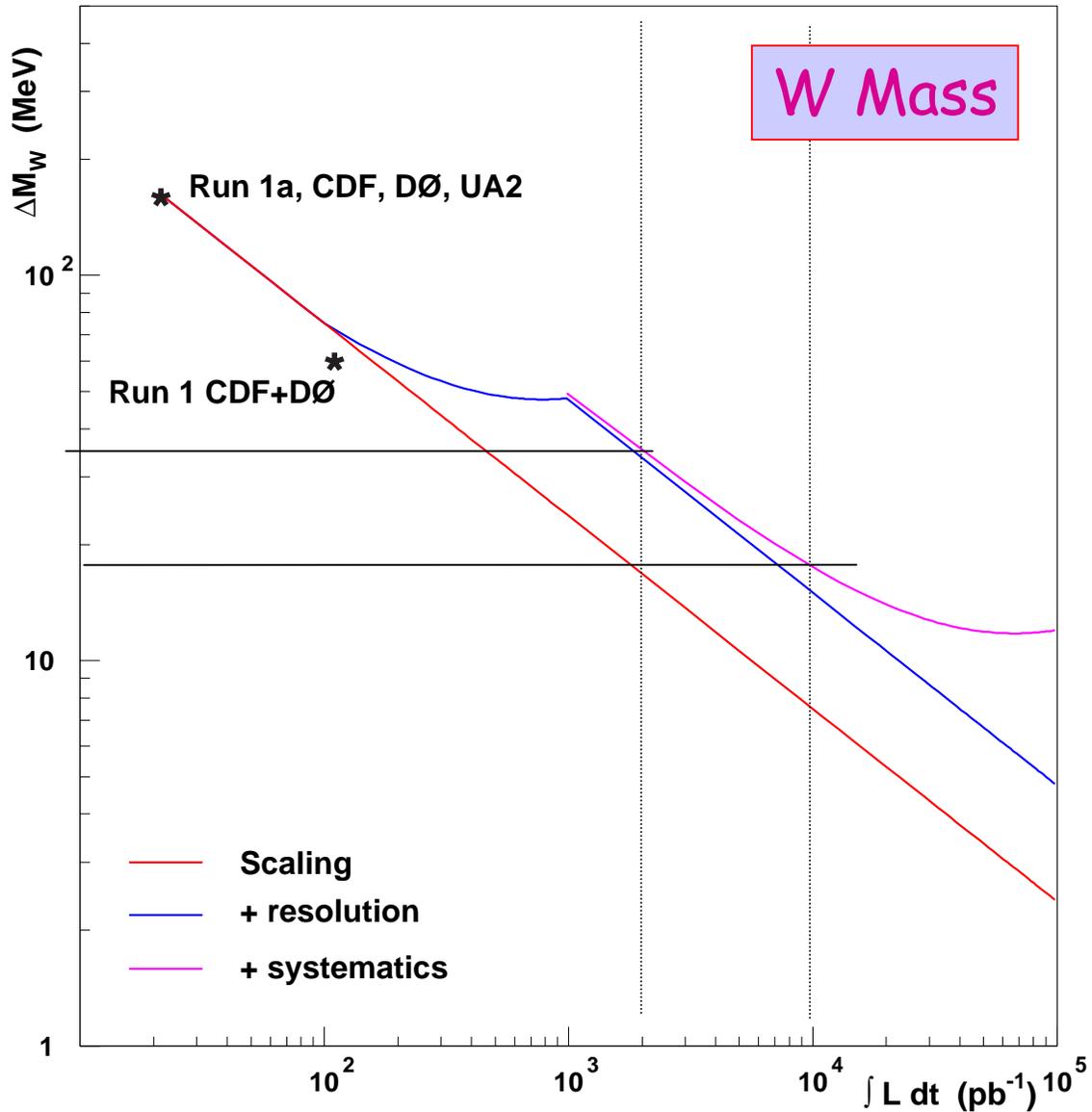


Tevatron Expectations

- **SM Higgs: CDF \oplus DØ**
 - Exclude $M_H < 180 \text{ GeV}$ (10 fb⁻¹/exp)
 - 3σ : $M_H < 180 \text{ GeV}$ (20 fb⁻¹/exp)
 - 4σ : $M_H < 125$ and $150 < M_H < 170 \text{ GeV}$
(20 fb⁻¹/exp)
- **SUSY**
 - Substantial portion of parameter space.
- **M_W : CDF \oplus DØ**
 - $\sigma_M \sim 35 \text{ MeV}$ (2 fb⁻¹/exp)
 - $\sigma_M < 20 \text{ MeV}$ (10 fb⁻¹ /exp)
- **M_t : CDF or DØ individually**
 - $\sigma_M < 4 \text{ GeV}$ (2 fb⁻¹/exp)
 - $\sigma_M < 2 \text{ GeV}$ (10 fb⁻¹/exp)
- **B Physics : CDF estimates**
 - $\delta\sin 2\beta \sim 0.07$ (2 fb⁻¹)
 - $\delta\sin 2\beta \sim 0.02$ (15 fb⁻¹)
 - B_s mixing: $x_s < 50$ (2 fb⁻¹)



Tevatron W & top masses

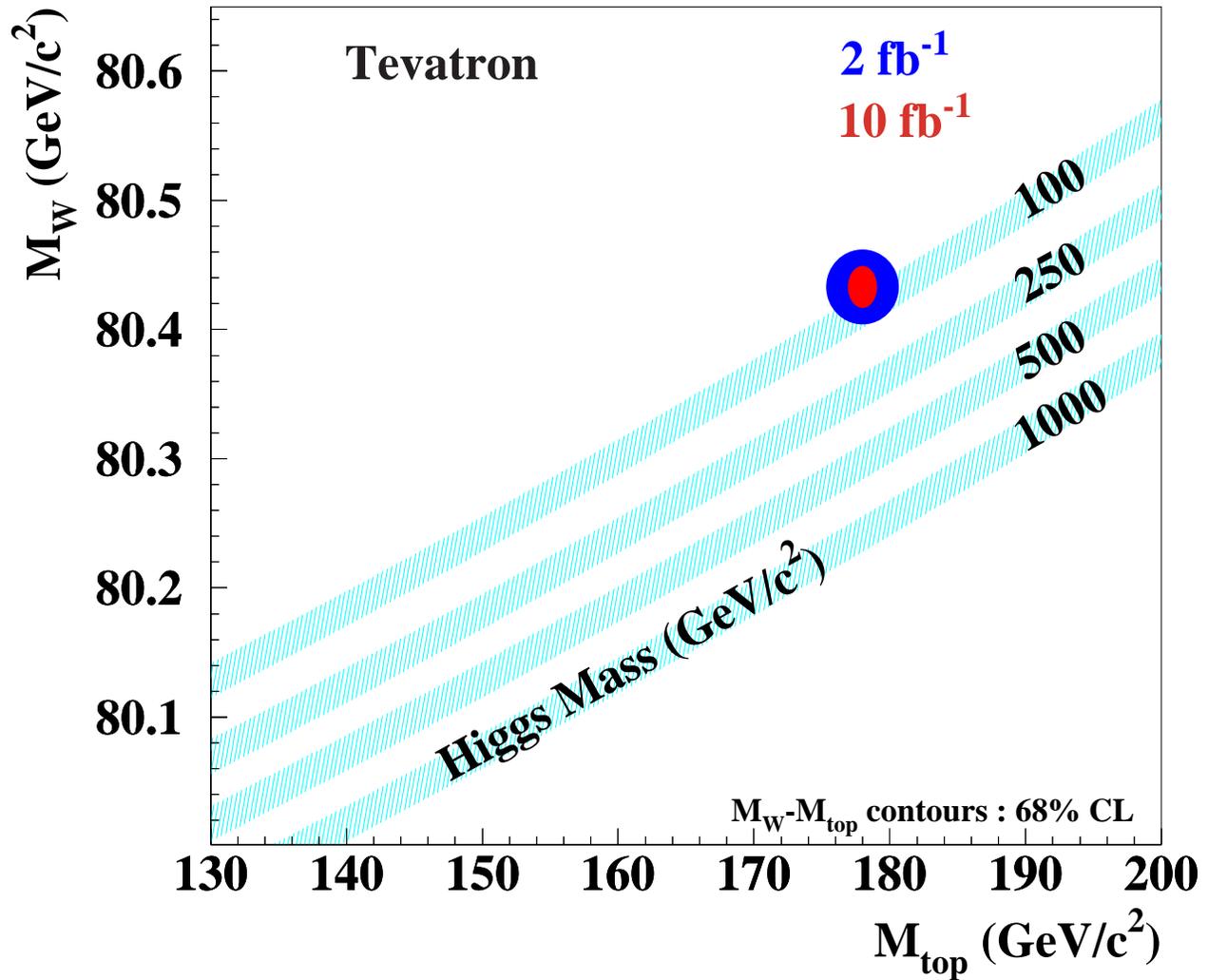


- **Top Mass**

- $2 \text{ fb}^{-1} \Rightarrow \delta m \sim 4 \text{ GeV}$ per experiment
- $10 \text{ fb}^{-1} \Rightarrow \delta m \sim 2 \text{ GeV}$ per experiment



Tevatron Electroweak





Tevatron B Physics

- Run 1 CDF: $\sin 2\beta = 0.8 \pm 0.4$
- Run 2 CDF: ± 0.07 (0.02) for 2 (15) fb^{-1}
- $\sin 2\alpha$ w/ $B \rightarrow \pi\pi$ and γ w/ $B \rightarrow DK$
- x_s with very high precision

